2017

# Exploration of the Southern California Borderland

Marie-Helene Cormier
*University of Rhode Island*, milenecormier2@gmail.com

Katherine L. C. Bell
*University of Rhode Island*

***See next page for additional authors***



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**Authors**
Marie-Helene Cormier, Katherine L. C. Bell, Stephanie M. Sharuga, Chris Castillo, James Conrad, Diva Amon, Mark Legg, Michael L. Brennan, Kelsey Barnhill, Lawrence L. Lovell, Ashley Marrazino, Simon L. Klemperer, and Renato Kane

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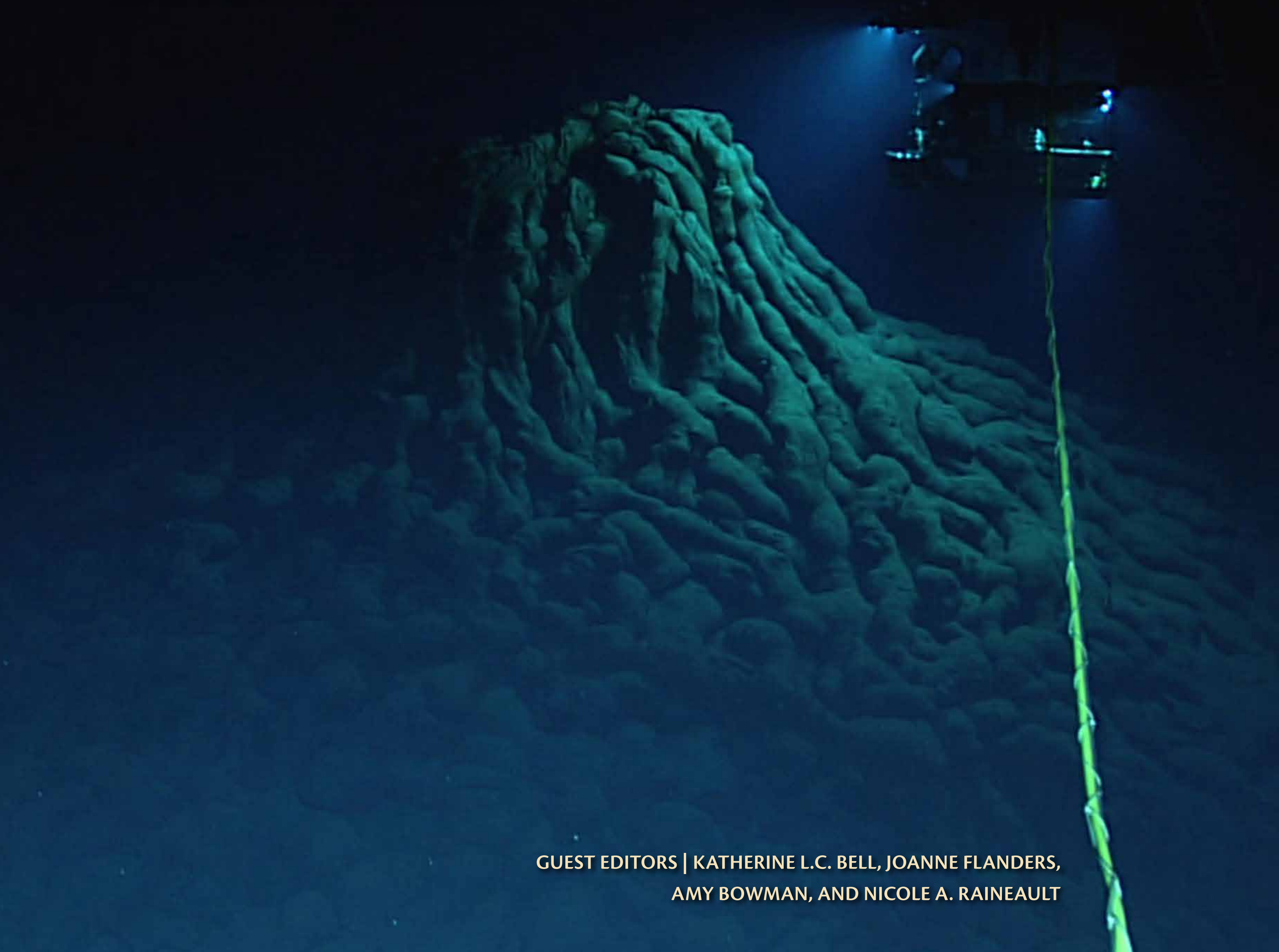
# New Frontiers in Ocean Exploration

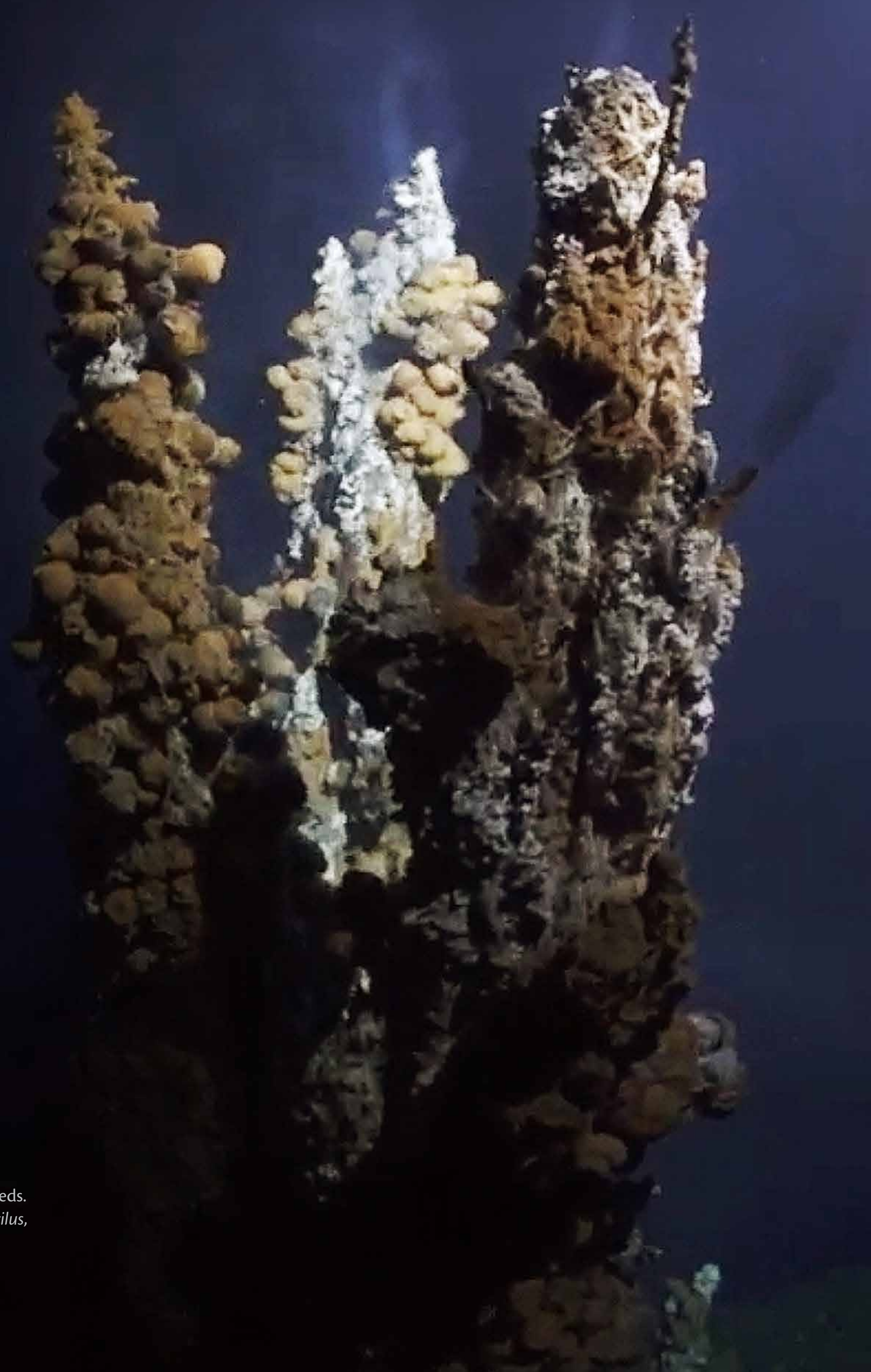
The E/V *Nautilus*, NOAA Ship *Okeanos Explorer*, and R/V *Falkor* 2016 Field Season



GUEST EDITORS | KATHERINE L.C. BELL, JOANNE FLANDERS, AMY BOWMAN, AND NICOLE A. RAINEAULT

FRONT COVER. ROV *Deep Discoverer* explores an eruptive vent at the top of a large mound of pillow lavas during the 2016 *Deepwater Exploration of the Marianas* expedition. *Photo credit: NOAA OER*

THIS PAGE. ROV *ROPOS* image showing chimney structures at a black smoker hydrothermal vent. *Photo credit: SOI/ROPOS*

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# Contents

**Introduction** 1

**2016 Expedition Overview Map** 4

**Ocean Exploration Trust – E/V *Nautilus***

Technology 6

*Nautilus* as a Testbed for Experimental Technologies 12

Upgrades to the *Nautilus/Hercules* Software Systems 14

*Nautilus* Samples 2016: New Techniques and Partnerships 15

*Nautilus* Education & Outreach Programs 18

*Nautilus* Field Season Overview 24

- *Wiring the Abyss* 2016: Ocean Networks Canada's Most Challenging Expedition 26
- Water Column and Cold Seep Exploration of the Cascadia Margin 28
- Exploration of S/S *Coast Trader* 31
- Mapping and Exploration of Deep-Sea Corals and Shipwrecks in the Greater Farallones National Marine Sanctuary 32
- Exploration and Mapping of USS *Independence* 34
- Exploration of Central California Basins, Cold Seeps, and San Juan Seamount 36
- Mapping and Exploration Within and Surrounding the Channel Islands National Marine Sanctuary 38
- Exploration of the Southern California Borderland 40

**NOAA Office of Ocean Exploration and Research**

Exploration and Information to Meet National Needs with NOAA Ship *Okeanos Explorer* 42

New Technologies for Ocean Mapping 43

Telepresence: Sending Imagery from the Seafloor to Your Screen 46

Exploring the Ocean Through Data 48

Value to the Nation: Surveying and Data Management for the US Extended Continental Shelf Project 50

Combined Bathymetry Coverage in the Mariana Region 52

CAPSTONE: Exploring the US Marine Protected Areas in the Central and Western Pacific 53

- 2016 Hohonu Moana: Exploring the Deep Waters off Hawai'i 56
- Combined Bathymetry Coverage of the Hawaiian Archipelago and Pacific Remote Islands Marine National Monument 58
- Deepwater Exploration of the Marianas 60
- The 2016 Midwater Exploration of the Mariana Region 66
- First Deep Exploration in the Wake Unit of the Pacific Remote Islands Marine National Monument 68
- Exploring the Underwater Archaeology of World War II 72

Hidden Ocean: Exploring the Dynamic Chukchi Borderlands 74

Engagement 2016: A Commitment Reaching Far and Wide 76

**Schmidt Ocean Institute – R/V *Falkor***

A Glance at Schmidt Ocean Institute 78

- An Introduction 78
- R/V *Falkor* 2016 Field Season 79
- Global Networks – Sharing Science and Partnership Projects 82

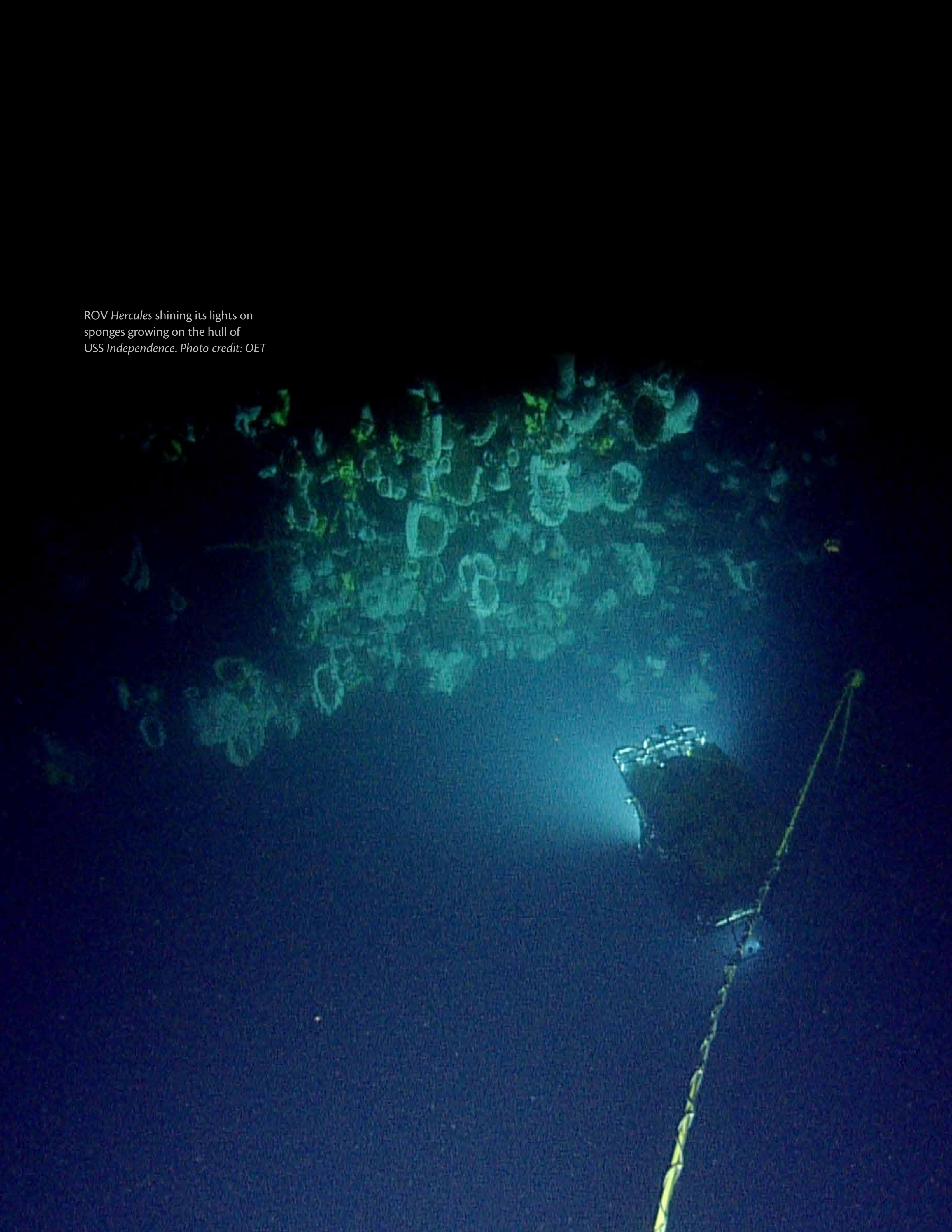
**Epilogue** 84

Authors 86

Acknowledgments 88

References 92

Acronyms 94



ROV *Hercules* shining its lights on sponges growing on the hull of USS *Independence*. *Photo credit: OET*

# Introduction

By Katherine L.C. Bell, William Mowitt, and Victor Zykov

Welcome to the seventh ocean exploration supplement to *Oceanography*! In addition to the initial results of the Exploration Vessel (E/V) *Nautilus* and National Oceanic and Atmospheric Administration (NOAA) Ship *Okeanos Explorer* 2016 expeditions, we are very pleased this year to include highlights of several projects that took place aboard Research Vessel (R/V) *Falkor,* as provided by guest contributor Schmidt Ocean Institute (SOI). In 2016, the three programs focused their efforts in the largest ocean basin on the planet—*Falkor* in the southern and western Pacific, *Okeanos Explorer* in the central and western Pacific, and *Nautilus* in the eastern Pacific. Here, we include summaries of research, exploration, and discoveries, describing new developments in technology and engineering, as well as innovative education and outreach approaches for learners around the globe.

Continuing its mission of ocean exploration, innovation, and education, the Ocean Exploration Trust (OET) embarked on the eighth field season of E/V *Nautilus*. This section of the supplement begins with a catalog of *Nautilus*' technical capabilities (pages 6–11), as well reports on new experimental technologies that were deployed at sea (pages 12–13), upgrades to the software systems of the remotely operated vehicles (ROVs) *Hercules* and *Argus* (page 14), and new techniques and results for sample collection and analysis (pages 15–17). Next, we describe OET's global efforts for increasing interest and literacy in science, technology, engineering, and mathematics (STEM) fields by harnessing the public's excitement about ocean exploration (pages 18–23). Finally, we report on the results of the 2016 *Nautilus* field season's geological, biological, and archaeological exploration off the west coast of North America, from British Columbia to southern California (pages 24–41). Several of the nine cruises were undertaken in partnership with the NOAA Office of National Marine Sanctuaries and Pacific Marine Environmental Laboratory, and the results are being used to support NOAA priorities in the region. The *Nautilus* team looks forward to continuing to grow these and other relationships in 2017 and beyond.

The second section focuses on the advances and accomplishments of NOAA Ship *Okeanos Explorer*, as well as other exploratory efforts by the NOAA Office of Ocean Exploration and Research (OER). We begin with a description of the technologies and innovations used for ocean exploration, including telepresence, ocean mapping, and managing and expanding access to oceanographic video and data, as well as the important work of the US Extended Continental Shelf Project (pages 42–52). Next, we focus on the results of field projects, most of which were carried out aboard *Okeanos Explorer* under the auspices of the Campaign to Address Pacific monument Science, Technology, and Ocean NEeds (CAPSTONE; pages 53–73). The CAPSTONE campaign included deep-sea mapping and imaging along with biological and geological exploration of the Hawaiian Archipelago, Mariana Islands, and remote Pacific islands, including Wake Island. This campaign included World War II-related underwater archaeology. We also report on the findings of the exploration of the Chukchi Borderlands and Glacier Bay National Park and Preserve (pages 74–75). Affirmation of OER's continued commitment to encourage the next generation of ocean explorers, scientists, and engineers through public engagement and education closes the section (pages 76–77).

In the third and final section of this supplement, we highlight several research projects supported by Schmidt Ocean Institute in 2016. SOI strives to advance the frontiers of global marine research by providing state-of-the-art operational, technological, and informational support to pioneering ocean science and technology projects at sea. In 2016, SOI supported studies of oxygen minimum zones; high-resolution mapping of hydrothermal vents in three dimensions; and investigation of physical, chemical, and microbial processes in the air-sea microlayer, as well as other projects in the South China Sea near Hawaiʻi (pages 78–83). With its philanthropic efforts, SOI aims to demonstrate how scalable innovation can tackle important scientific and societal challenges.

All three programs are continuing their important work in the Pacific Ocean in 2017, and we look forward to sharing our discoveries with you.

# The Value of Marine Protected Areas to the Nation

By James P. Delgado, Mitchell Tartt, Matthew Stout, Katie Wagner, and Sarah Marquis

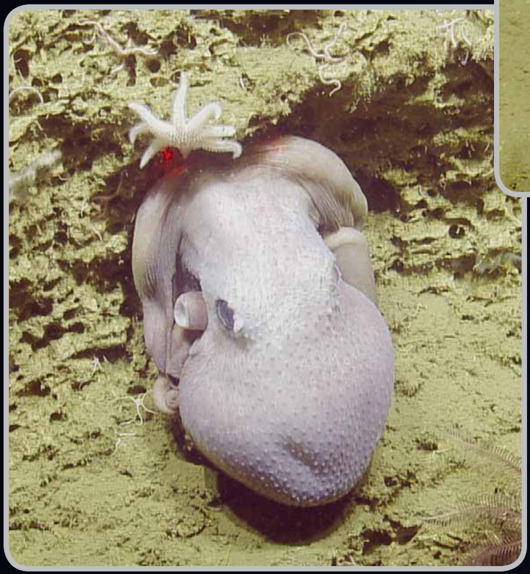
Marine protected areas (MPAs) are vital tools for conserving the ocean's most unique and valuable resources. MPAs cover 3.2 million square kilometers (26%) of US marine waters, and protect nationally important marine resources, including fish, minerals, and a rich record of human history (NOAA, 2017a).

The US National Marine Sanctuary System includes 13 national marine sanctuaries (NMS) and two of the four US marine national monuments within the US Exclusive Economic Zone (EEZ) and Great Lakes. Across all national marine sanctuaries, approximately $8 billion is generated annually in local coastal- and ocean-dependent economies from activities such as commercial fishing, research, and recreation (NOAA, 2017b). This figure does not include the net economic value—the value received by a consumer of a good or service over and above what the consumer is required to actually pay to receive the good or service. The estimated net economic value of the Main Hawaiian Islands coral reefs alone is $33.57 billion (Bishop et al., 2011).

While scientists knew enough about these places to inform the process that made them sanctuaries and monuments, much remains to be learned. The nation's ocean exploration program therefore includes a focus in and near MPAs. In 2016, E/V *Nautilus* explored and documented five West Coast sanctuaries (pages 32–39), NOAA Ship *Okeanos Explorer* focused on US MPAs in the central and western Pacific (pages 53–73), and R/V *Falkor*'s work ranged from the tropical to the western Pacific, including the Marianas Trench Marine National Monument (page 81).

These expeditions increased US knowledge of MPAs and laid a foundation upon which further work can be built. The expeditions' use of telepresence brought together scientists and the public to watch dives as they were being conducted and to participate in exploration of the deep sea in real time. Whether the ships were far out in the Pacific or near coastal communities, the larger community saw that discovery and learning were happening in US waters. Social media, live-streamed Internet broadcasts, special educational programs, and news stories shared the process of exploration and the discoveries that underscored why marine protected areas are valuable, and they told the stories that continue to emerge from the depths of these valuable and unique places.

Octocoral *Anthomastus* spp., Farallones Escarpment. *Photo credit: OET*



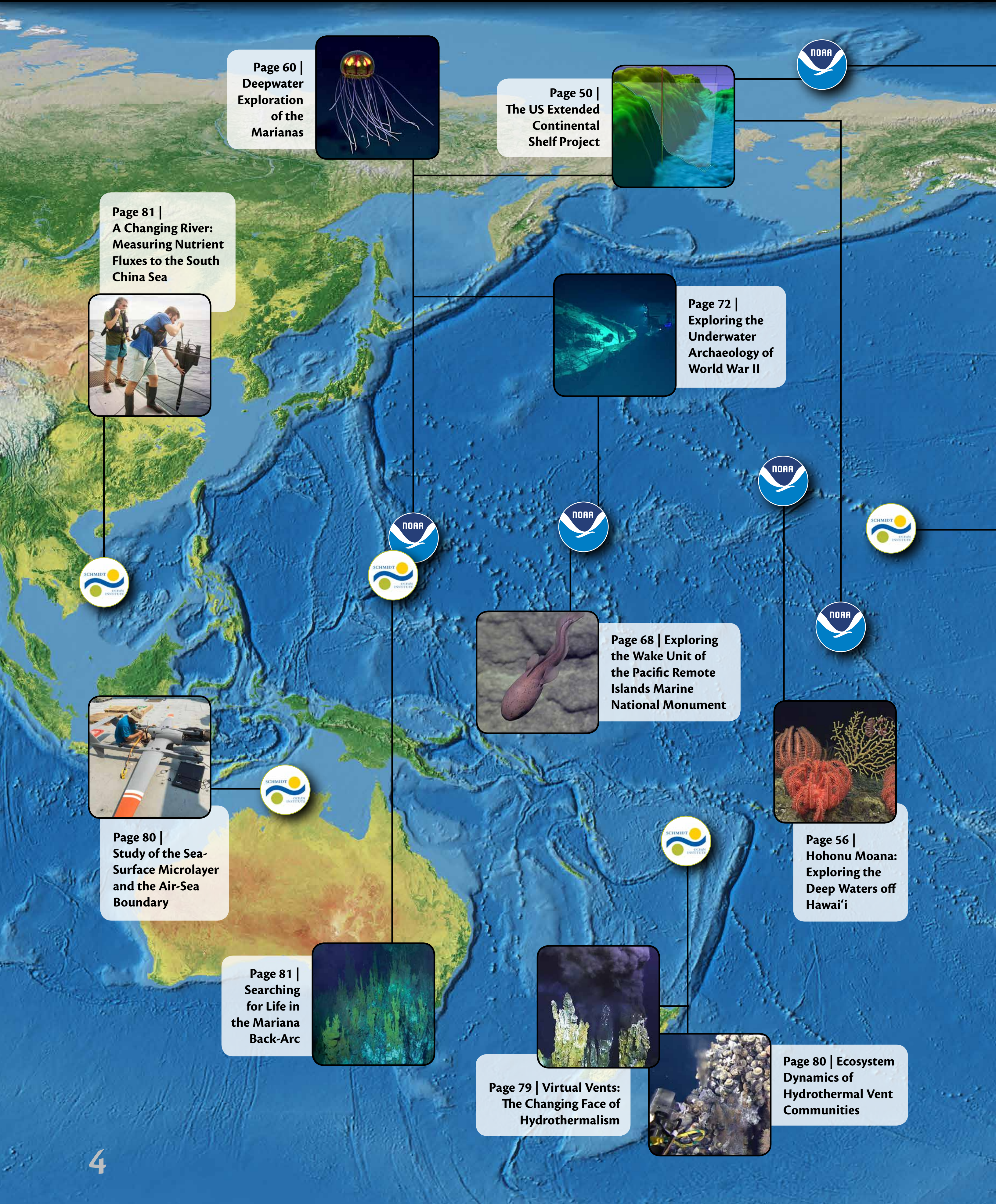
Octopus, Farallones Escarpment. *Photo credit: OET*

Farallones Escarpment habitat.
*Photo credit: OET*

Bubble gum coral, Farallones Escarpment. *Photo credit: OET*

One of the unusual benthic platyctenid ctenophores documented during an ROV dive at Ahyi Seamount in the Marianas. *Photo credit: NOAA OER*

# 2016 Expedition Overview Map



E/V *Nautilus* Expeditions

NOAA Office of Ocean Exploration and Research Expeditions

R/V *Falkor* Expeditions

# Technology

## E/V *Nautilus*

*Nautilus* is an efficient 64-meter exploration vessel with 17 permanent crew and berthing for a 31-member rotating Corps of Exploration. The ship is equipped with a Kongsberg EM 302 multibeam echosounder and two ROVs named *Hercules* and *Argus* that explore the seafloor. The ship has a data lab and wet lab, as well as other scientific facilities, for processing digital data and physical samples. As part of our effort to share our expeditions with students and colleagues, we use telepresence technology to stream live video from our ROVs and various locations on the ship in real time to our Nautilus Live website (http://www.nautiluslive.org).

### GENERAL

BUILT | 1967, Rostock, Germany

LENGTH | 64.23 meters (211 feet)

BEAM | 10.5 meters (34.5 feet)

DRAFT | 4.9 meters (14.75 feet)

TONNAGE | 1,249 gross, 374 net

RANGE | 24,000 kilometers (13,000 nautical miles) at 10 knots

ENDURANCE | 40 days at sea

SPEED | 10 knots service, 12 knots maximum

FUEL CAPACITY | 330 cubic meters

PROPULSION | Single 1,285 kilowatt (1,700 hp) controllable pitch main thruster; 280 kW bow tunnel thruster; 300 kW jet pump stern thruster

SHIP SERVICE GENERATORS | Two 585 kVA generators, one 350 kVA generator

PORTABLE VAN SPACE | One 20-foot van

COMPLEMENT | 17 crew; 31 science and operations

FLAG | St. Vincent and the Grenadines

HEAVY EQUIPMENT |

- Dynacon 421 ROV winch with 4,500 meter (14,764 feet) Rochester A06063 1.73 centimeter (0.681 inch) diameter cable
- DT Marine 210 winch with 1,200 m Rochester A320327 0.82 centimeter (0.322 inch) diameter wire
- Bonfiglioli knuckle-boom crane, 2–6 ton capacity, two extensions
- Two airtuggers, SWL 900 lbs each
- A-frame, SWL 8 mtns
- Rescue boat davit with SWL 0.9 mtn
- Oceanscience UCTD 10-400 profiling system; max depth 1,000 meters

### TELEPRESENCE TECHNOLOGY

VSAT | 2.4 meter axis stabilized Sea Tel 9711 uplink antenna capable of C- and Ku-band operation of up to 20 Mbps (C-band circular or linear)

REAL-TIME VIDEO STREAMING |

- Three Tandberg standard definition encoders with multiplex for encapsulating real-time video
- Harmonic Electra 7000 high-definition encoder

CAMERAS | Two Sony BZR-H700 high-definition pan/tilt/zoom cameras mounted to view the aft deck and port rail; one BZR-H700 in the control vans; Marshall VS-570 PTZ cameras in the wet lab and in the ROV hanger

*Photo credit: Ocean Networks Canada*

*Note: All images in the* Nautilus *section of this publication are copyright OET unless otherwise indicated.*

COMMUNICATIONS |
- Ship-wide RTS Telex intercom system for real-time communications between ship and shore
- Handheld UHF radios are interfaced with the RTS intercom system for deck, bridge, and Control Room communications
- Telephone interface is available through a Rhode Island exchange for real-time collaboration between scientists ashore and on the ship
- Full Internet connectivity from shipboard LAN and wifi

## DATA PROCESSING & VISUALIZATION LAB

AREA | 44.5 square meters (480 square feet)

WORKSTATIONS | Seven workstations for data manager, data loggers, navigators, educators, data engineers, satellite engineer, video engineer; seafloor mapping data processing; flexible bench space

## RACK ROOM

AREA | 17.3 square meters (185 square feet)

VIDEO STORAGE | Two Omneon Mediadecks (MDM-5321 and SMD-2200-BB) for video recording and storage

DATA STORAGE | 16 TB online storage for non-video data; 28 TB disk storage for video data

EMERGENCY COMMUNICATIONS | Two Iridium phones

ELECTRONICS WORKBENCH | 80 cu ft of storage

## PRODUCTION STUDIO

AREA | 12 square meters (130 square feet)

CAMERA | Remote controllable high-definition Sony BRC-H700, Canon FX-305 for live deck television broadcasts and interactions

SWITCHER | Ross CrossOver16 with ability to switch underwater, topside, or scaled computer video streaming to the Inner Space Center for live interactions

## WET LAB

AREA | 19 square meters (204.5 square feet) with 5-meter-long (16-foot) stainless steel worktop

REFRIGERATION |
- Panasonic MDF-C8V1 ULT –80/–86°C scientific freezer, 0.085 cubic meters (3 cubic feet)
- Science refrigerator/freezer, approximately 0.57 cubic meters (20 cubic feet)

HAZMAT |
- Fume hood
- HAZMAT locker for chemical and waste storage
- Carry-on, carry-off chemical policy

## ROV HANGAR

AREA | 24 square meters (258.3 square feet)

POWER | 110/60 Hz and 220/50 Hz available

PERSONAL PROTECTIVE EQUIPMENT | Hard hats, PFDs, high voltage gloves

LIFTS | 2 × 2-ton overhead manual chainfall lifts

STORAGE | Storage for spares and other equipment

## ROV WORKSHOP

AREA | 18 square meters (193.8 square feet)

TOOLS | Complete set of hand tools, cordless tools, electrical and fiber optic test equipment, mill-drill combination machine

STORAGE | Storage for spares and other equipment

## CONTROL & IMAGING VANS

AREA | 28 square meters (301.4 square feet)

WORKSTATIONS | Nine; typical configuration for ROV operations: two to three scientists, data logger, *Hercules* pilot, *Argus* pilot, navigator, video engineer, educator

# Acoustic Systems

## KONGSBERG EM 302 MULTIBEAM ECHOSOUNDER

The EM302 is a hull-mounted 30 kHz multibeam echosounder composed of two long transducer arrays mounted in a T-shape on the hull of *Nautilus*. It was installed on the ship in 2012/2013 to collect bathymetric, backscatter, and water column data. This information is useful for identifying areas or features of interest, creating bathymetric charts for ROV dive planning and situational awareness, and locating hydrothermal vents and gas or oil seeps. The EM302 can efficiently map the seafloor in water depths from 10 m to 7,000 m (33 ft to 22,965 ft) at ship speeds of 8–10 knots.

FREQUENCY | 30 kHz

DEPTH RANGE | 10–7,000 meters (33–22,966 feet)

PULSE FORMS | CW and FM chirp

BEAMWIDTH | 1° × 1°

APPROXIMATE SWATH WIDTH | 3–5 times water depth, up to 8 km (5 miles)

APPROXIMATE GRID RESOLUTION | 10% water depth (e.g., 10 meters [33 feet] at 1,000 meters [3,281 feet] depth)

## KNUDSEN SUBBOTTOM PROFILER AND ECHOSOUNDER

The Knudsen 3260 is a subbottom echosounder mounted inside the hull of *Nautilus*. It operates at low frequencies (3.5–210 kHz) so that the sound it emits can penetrate layers of sediment. The sound that bounces back is captured by the system, allowing creation of cross sections of the seafloor. Scientists can use the data to identify subsurface geological structures such as faults and ancient channels and levees. The Knudsen 3260 can operate in full ocean depths. The Knudsen system also collects 15 kHz single beam sonar data.

PROFILER | Knudsen 3260 Chirp subbottom profiler and echosounder

OPERATING FREQUENCY | Dual frequency, 3.5 kHz and 15 kHz

POWER | 4 kW on Channel 1 and up to 2 kW on Channel 2

RANGE | 50 to 5,000 meters (164 to 16,404 feet)

## ULTRA-SHORT BASELINE NAVIGATION SYSTEM

SYSTEM | TrackLink 5000MA system for USBL tracking of ROVs *Hercules* and *Argus*

RANGE | Up to 5,000 meters (16,404 feet)

POSITIONING ACCURACY | 1° (~2% of slant range)

OPERATIONAL BEAMWIDTH | 120°

OPERATING FREQUENCY | 14.2 to 19.8 kHz

TARGETS TRACKED | *Hercules*, *Argus*, and two additional transponders are available. With more transponders, up to eight targets including the ROVs can be tracked

# Remotely Operated Vehicle *Argus*

ROV *Argus* was first launched in 2000 as a deep-tow system capable of diving to 6,000 meters. More recently, *Argus* is used in tandem with ROV *Hercules*, where it hovers several meters above in order to provide a bird's-eye view of *Hercules* working on the seafloor. *Argus* is also capable of operating as a stand-alone system for large-scale deepwater survey missions.

## GENERAL

DEPTH CAPABILITY | 6,000 meters (19,685 feet), currently limited to 4,000 meters

CABLE | 4,500 meters (14, 764 feet), 0.681 electro-optical, 3x #11 conductors, 3x SM fibers

SIZE | 3.8 meters long × 1.2 meters wide × 1.3 meters high

WEIGHT | 2,100 kilograms (4,700 pounds) in air

MAXIMUM TRANSIT SPEED | 2 knots

ASCENT/DESCENT RATE | 20–30 meters/minute (65–98 feet/minute) max

PROPULSION | Two Deep Sea Systems International 404 brushless DC thrusters for heading control

## IMAGING & LIGHTING

CAMERAS |

- One Insite Pacific Zeus Plus high-definition camera with Ikegami HDL-45A tilt head with Fujinon HA 10 × 5.2 lens – 1080i SMPTE 292M output format – 2 MP still image capable
- Two Insite Pacific standard definition mini utility cameras (fixed mounted) 480 line NTSC format
- One Deep Sea Power & Light Wide-i SeaCam, downward-looking standard definition camera (fixed mounted)

LIGHTING |

- Four CathX Aphos 16 LED lampheads, 28,000 lumens each
- Two Deep Sea Power & Light 250 Watt incandescent lights

## VEHICLE SENSORS & NAVIGATION

SYSTEM | NavEst integrated navigation system solution

USBL NAVIGATION | TrackLink 5000 system, acoustically triggered

PRIMARY HEADING | Crossbow high-resolution magnetic motion and attitude sensor

SECONDARY HEADING | TCM2 solid state fluxgate compass

PRESSURE SENSOR | Paroscientific Digiquartz 8CB series

ALTIMETER | Benthos PSA-916

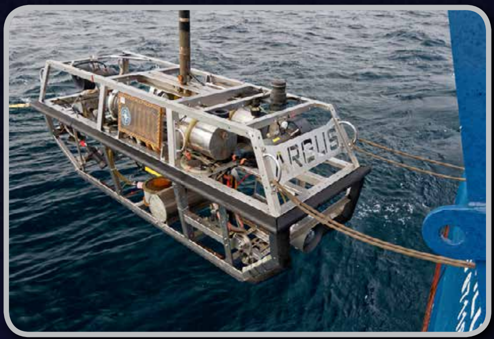
FORWARD-LOOKING SONAR | Mesotech 1071, 675 kHz, 0.5–100 meter range typical

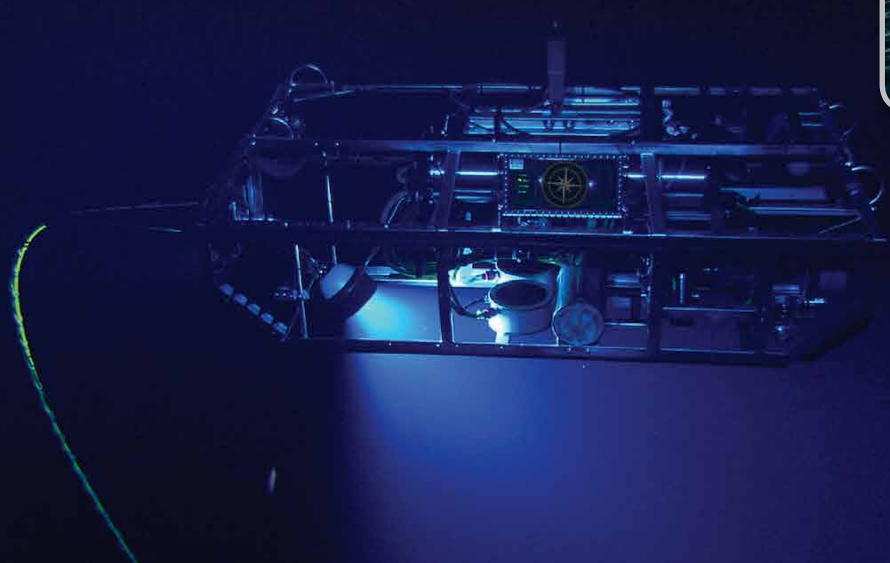
SUBBOTTOM PROFILING SONAR | TriTech SeaKing Parametric Subbottom Profiler (10–30 kHz)

## SCIENTIFIC INSTRUMENT SUPPORT

POWER | 110 V 60 Hz AC, 24 VDC and 12 VDC power options

DIGITAL DATA CHANNELS | RS-232





# Remotely Operated Vehicle *Hercules*

Since it was first launched in 2003, ROV *Hercules* has been working in tandem with ROV *Argus* to explore the geology, biology, archaeology, and chemistry of the deep sea. *Hercules* is equipped with a high-definition video camera, several LED lights, two manipulator arms, and a variety of oceanographic sensors and samplers, including a suite of high-resolution mapping tools that is available for use upon request. *Hercules* can deliver approximately 68–136 kg (150–300 lbs) of samples or tools to and from the seafloor.

## GENERAL

DEPTH CAPABILITY | 4,000 meters (13,123 feet)

TETHER | 30–45 meters (98.4–147.6 feet), 20 millimeters (0.79 inches) diameter, neutrally buoyant

SIZE | 3.9 meters long × 1.9 meters wide × 2.2 meters tall (12.8 feet long × 6.2 feet wide × 7.2 feet tall)

MASS | ~ 2,500 kilograms (5,500 pound-mass) in air

PAYLOAD | Up to 136 kilograms (300 pounds)

MAXIMUM VEHICLE SPEED | 0.77 meters/second (1.5 knots) forward, 0.25 meters/second (0.5 knots) lateral, 0.5 meters/second (1 knot) vertical (on site, within tether range)

MAXIMUM TRANSIT SPEED | 1 meter/second (2 knots), no sampling, in layback mode

MAXIMUM ON-BOTTOM TRANSIT SPEED | 0.5 meters/second (1 knot), no sampling

MAXIMUM SAMPLING TRANSIT SPEED | 0.25 meters/second (0.5 knots) on flat seafloor; < 0.13 meters/second (< 0.25 knots) over featured terrain

ROV CLOSED LOOP POSITION CONTROL | Station Keep, X/Y step, Auto Depth, Auto Altitude, X/Y/Z step and hold velocity control

DESCENT/ASCENT RATE | 30 meters/minute (98.4 feet/minute), 20–22 meters/minute average

PROPULSION |

- Six hydraulic thrusters powered by 15 kW (20 hp), 207 bar (3,000 psi) hydraulic system
- Fore/Aft & Vertical – Four 27.94 cm (11 inch) ducted thrusters, each providing 900 N (200 lbf) thrust
- Lateral – Two 22.86 cm (9 inch) ducted thrusters, each providing 450 N (100 lbf) thrust

## VEHICLE SENSORS & NAVIGATION

SYSTEM | NavEst integrated navigation system solution

HEADING AND ATTITUDE |

- Primary Heading – IXSEA Octans III north-seeking fiber-optic gyrocompass (0.1° secant latitude accuracy with 0.01° resolution)
- Secondary Heading – TCM2 solid state fluxgate compass

PRESSURE SENSOR | Paroscientific Digiquartz 8CB series

CTD | Sea-Bird FastCAT 49

OXYGEN OPTODE | Aanderaa 3830

TEMPERATURE PROBE | WHOI high-temperature probe (0°–450°C, 0.1°C resolution)

USBL NAVIGATION | TrackLink 5000

DOPPLER NAVIGATION & ALTITUDE | RDI Workhorse Navigator Doppler Velocity Log 600 kHz, 0.7–90 meter range (2.3–295.3 feet)

FORWARD-LOOKING SONARS |

- Kongsberg Mesotech 1071 scanning sonar, 300 kHz, 1–200 meter (3–656 feet) range typical
- TriTech Super SeaPrince 675 kHz, 50 meter (164 feet) range

## IMAGING & LIGHTING

STANDARD IMAGING SUITE | One high-definition video channel on fiber optic, four standard definition video channels on coax, generally configured as:

- Insite Pacific, 6,000 msw rated, Zeus Plus with 10× zoom lens, Ikegami HDL-45A with zoom/pan/tilt/extend –1080i SMPTE 292M output format
- Insite Pacific, 6,000 msw rated, Titan Rotate-Tilt standard definition camera (bubble camera) 480 line NTSC format
- Three Insite Pacific NOVA utility cameras, mounted to view the starboard sample box, 480 line NTSC format
- One Insite Pacific Aurora utility camera to view the eight-jar suction sampler, NTSC format
- One Deep Sea Power & Light Wide-i-SeaCam to view starboard side sample box, NTSC format

LIGHTING |

- Two Deep Sea Power & Light Matrix-3 LED lamps, 20,000 lumens, forward mounted
- Six to twelve Deep Sea Power & Light Sphere LED lamps, 6,000 lumens, mounting configurable

SCALING | Two red Deep Sea Power & Light Micro Sea-Lasers, mounted 10 cm (3.94 inches) apart, HD camera only

HIGH-RESOLUTION MAPPING SUITE |

- Available for nonstandard mapping products
- Typical configuration is downward looking; custom configurations possible
- 1375 kHz BlueView multibeam, 90° total swath, 10 meter range, centimeter resolution capable
- Two stereo Prosilica still cameras, one black & white, one color; 1,024 × 1,360 pixels; 29° × 39° field of view; 2–4 meter (6.5–13 feet) range; 100 Watts strobe lighting at 1 image/3 seconds
- Experimental structured light laser system with dedicated still camera; runs concurrently with stereo imaging; 532 nanometers; 100 mW; 45° line generating head; inclined plane
- Raytrix R5 lightfield camera available as a custom configuration

## MANIPULATORS AND SAMPLING

MANIPULATORS |

- Kraft Predator: Hydraulic, seven function spatially correspondent, force feedback, 200 lb lift
- ISE Magnum: Hydraulic, seven function, 300 lbs lift

SUCTION SYSTEMS |

- Suction sampling system, eight 3-liter discrete samples
- Venturi dredge excavation system

SAMPLING TOOLS | Mission configurable

- Up to eight 6.35 centimeter (2.5 inch) inner diameter, 28 centimeter (11 inch) long push cores
- Up to six 5-liter Niskin bottles, manually triggered
- Custom tools can be integrated

SAMPLE STORAGE |

- Forward sample tray (inboard): 45 cm × 33 cm × 25 cm (17.7 inches × 13 inches × 9.8 inches)
- Forward sample tray (outboard): 68 cm × 35 cm × 30 cm (26.8 inches × 13.8 inches × 11.8 inches)
- Starboard sample drawer: 65 cm × 50 cm × 30 cm (25.5 inches × 19.7 inches × 11.8 inches)
- Payload: Up to 136 kilograms (300 pounds) depending on sensor package
- Custom configuration of boxes, crates, and containers

ELEVATORS | Mission configurable; free ascent; maximum standard payload 68 kg (150 lb)

## SCIENTIFIC INSTRUMENT SUPPORT

SWITCHED POWER |

- 110 V, 60 Hz AC
- 24 VDC

DIGITAL DATA CHANNELS |

- RS-232: 115 Kbauds
- RS-485/422: 2.5 Mbauds
- Ethernet: 10/100/1,000 Mbps links available
- TTL: one TTL link

HYDRAULIC | Proportional and solenoid hydraulic functions

- 1,150 psi at 10 GPM
- 1,850 psi at 10 GPM
- 3,000 psi at 10 GPM (advance notice needed)

EXAMPLES OF USER-INSTALLED SENSORS | Advance notice is required for custom solutions to engineering integration of user provided sensors and equipment.

- Harvard in situ mass spectrometer
- Fluorometer
- pH sensor
- PMEL MAPR eH sensor
- Kongsberg M3 multibeam sonar
- 18 MP Ethernet connected digital still camera

# *Nautilus* as a Testbed for Experimental Technologies

By Katherine L.C. Bell, Brennan Phillips, Kaitlyn Becker, Stephen Licht, Jifei Ou, Chin-Yi Cheng, Lining Yao, Misha Sra, Dhruv Jain, Don Blair, and Allan Adams

In 2016, E/V *Nautilus* and ROVs *Hercules* and *Argus* hosted several new types of exploration technologies, from innovations on collecting deep-sea samples to shooting (to the best of our knowledge) the first deep-sea 360° video. We present initial results of the work of researchers from Harvard University, University of Rhode Island, and Massachusetts Institute of Technology, who used OET's platforms as test beds for developing and evaluating new tools for exploration, science, and conservation.

## Squishy Robot Hands for Delicate Sample Collection

– Brennan Phillips and Kaitlyn Becker

Scientific ROVs such as *Hercules* are capable of performing extremely delicate manipulative tasks, thanks to the talented and experienced pilots who control state-of-the-art robotic arms. The growing field of soft robotics offers ways to augment deep-sea manipulation, allowing for delicate sample collection driven by simple hydraulic systems. The Harvard Microrobotics Laboratory has developed a soft robotic hand that runs on low-pressure seawater hydraulics and takes advantage of compliant construction materials to create inherently gentle and conformable gripping. This system was used during the Channel Islands cruise (pages 38–39) to collect biological specimens, including glass sponges, sea stars, holothurians, and a highly mobile decorator crab (Figure 1). Each specimen was carefully held and then returned to the seafloor without any apparent damage to the organism. Further development of the system is planned to include a coral cutter, wrist control, and other functionality, all based on seawater hydraulics.

Figure 1. A soft robotic hand is used to collect a holothurian from the seafloor at ~1,800 m in Arguello Canyon, California. The specimen was gently released, with no observed damage to the animal. *Photo credit: B. Phillips*

Figure 2. A "jamming" gripper is readied to collect a clam shell on Kimki Ridge at a depth of ~1,200 m.

## Compliant Gripper System – Stephen Licht

At the Robotics Laboratory for Complex Underwater Environments at the University of Rhode Island, we have been exploiting a phenomenon known as "particle jamming" to create tools that can transition back and forth between soft and rigid states. In the soft state, the tool can be pressed against an object so that a gripper membrane conforms to the shape of the object without damaging it. The pilot can then switch the gripper to the hard state, forming a rigid grasp with the right shape needed to pick up the object. We deployed a gripper system driven by a low-pressure hydraulic drive system on *Hercules,* demonstrating that the tool could be used to pick up man-made objects and a biological sample lying on soft sediment without damaging them, at depths of up to 1,200 m off southern California (pages 40–41; Figure 2). We also demonstrated that the strength of these grippers improves with depth. Grasping and pulling on a test sample identical to one in the lab, we recorded pull forces several times larger than anything possible at sea level, where the pressure drop cannot exceed one atmosphere.

## Open Ocean Data – Misha Sra, Don Blair, and Dhruv Jain

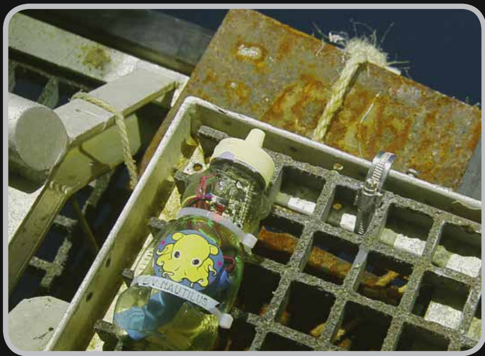


Figure 3. An open hardware temperature sensor (dubbed Honeybear) was given its first test aboard *Hercules*.

We deployed two open data technologies during the southern California cruise (pages 40–41). The first was a research workflow using Jupyter, a scientific computing platform that is built upon open web standards and open source software. Jupyter combines rich documentation with in-line, executable code to analyze and visualize data; the resultant "notebooks" can be easily modified, published, and shared. The intent of our second project was to enable rapid development of custom oceanographic instrumentation using an "open hardware" methodology for sharing instrument designs and schematics. Using inexpensive electronics along with tools in the *Nautilus* ROV shop, we improvised an accelerometer and a temperature sensor (Figure 3), each of which cost less than $100—orders of magnitude less than commercial instrumentation—but which performed comparably. We plan to build on the success of this deployment and to develop additional "open ocean science" instrumentation—tools that enable in situ, onboard innovation using available software and instrumentation, while also providing easy access points for collaboration and learning in laboratories and classrooms.

## Hygroscape – Jifei Ou, Chin-Yi Cheng, and Lining Yao

On the southern California cruise (pages 40–41), we deployed a kinetic scaffold designed to enhance restoration of coral reefs and other marine habitats. Our computationally generated, foldable scaffold can be transported as a flat piece and deployed as a three-dimensional structure underwater. It is parametric—that is, we can tune the unit sizes, surface areas, and material options as well as local structural stability in our software before it is physically constructed. During the cruise, we successfully assembled, deployed, and retrieved the structure as planned. This experience provided valuable lessons on the overall design and deployment process, and also helped us to understand the relationship between humans and the ocean. With these structures, we hope to create "open ocean farms" that will attract underwater organisms and allow them to grow within the structures, form new ecosystems, and also be free to circulate in the larger, open underwater world to create a "blue-green ecology."

Figure 4. A hygroscape was assembled on deck in three dimensions and then deployed flat, after which it unfolded approximately 95% of the way, demonstrating the feasibility of an underwater, unfolding structure. *Photo credit: K.L.C. Bell*

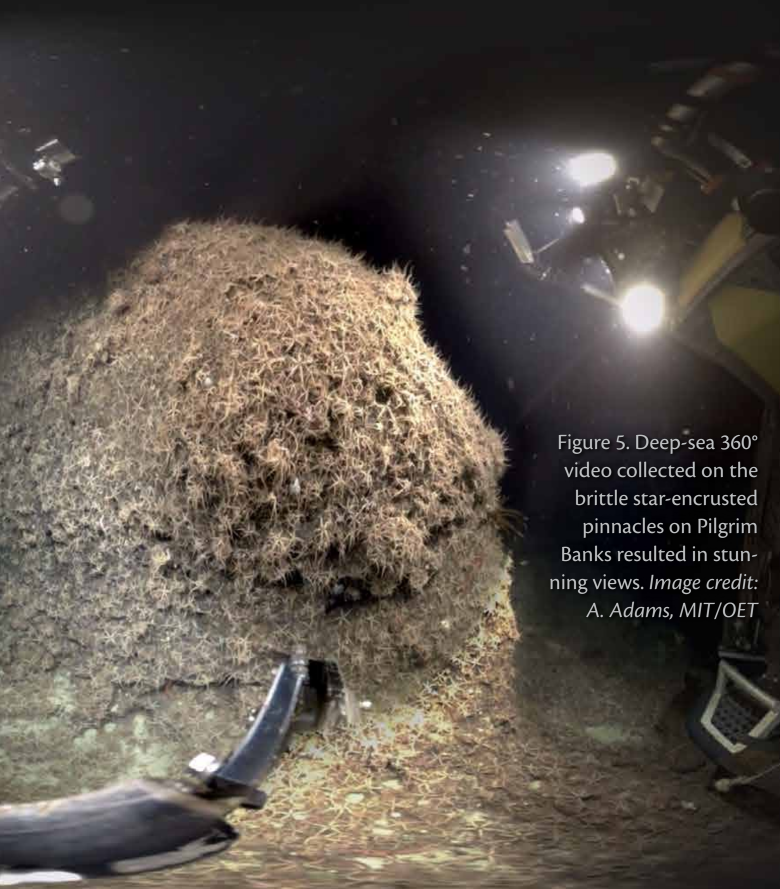


Figure 5. Deep-sea 360° video collected on the brittle star-encrusted pinnacles on Pilgrim Banks resulted in stunning views. *Image credit: A. Adams, MIT/OET*

## Deep Sea 360° – Allan Adams

Spherical video immerses viewers deep within a real-world scene, providing a powerful new tool for emotionally connecting people to otherwise inaccessible places and situations. To this end, I deployed a pair of slightly modified, commercially available underwater spherical cameras that are capable of safely diving to ~500 m on the southern California cruise (pages 40–41). Deploying the cameras on an ROV at such depths entailed numerous challenges, including lack of ambient light and the use of a magnetic wand to initiate recording underwater. Filming both on deck and beneath the waves gave us footage of vehicle launches and recoveries and a spectacular dive through pinnacles covered in brittle stars (Figure 5). We successfully tested the magnetic control on deck, and it is clear that the same system will work at depth. This expedition demonstrated that it is well worth the time and effort to build a camera rig with which to make gorgeous spherical images in the deepest parts of the ocean. The science, the visuals, and most importantly, the human stories of exploration are inspiring, and deserve serious artistic and technical effort.

# Upgrades to the *Nautilus/Hercules* Software Systems

By Jonathan Howland

In 2016, the Ocean Exploration Trust commissioned the replacement of key components of its robotic vehicle software suite, eliminating dependence upon legacy operating systems and positioning the system for continued effective use over the next decade.

When *Hercules* was first built in 2003, it relied upon modifications of several software systems originally developed by the Woods Hole Oceanographic Institution (WHOI) and collaborators at the Johns Hopkins University (Whitcomb et al., 2003). These software systems have been upgraded over the years to keep up with vehicle modifications. Portions of them, particularly the graphical user interfaces (GUIs), ultimately became challenging to support, due to the original use of Microsoft Windows-based development systems that are no longer supported or available.

The systems that needed replacement fell into two categories: pilot/engineer GUI and the navigation engine and user interface. The ROV controller and associated pilot/engineer GUI have followed a client/server model since their original development (Newman et al., 2008). Replacement of the GUI client was a relatively straightforward endeavor, because there was no real impetus to redesign the user experience (Figure 1). By using a modern open source multi-platform toolkit (QT) in the GUI replacement effort, the chance of obsolescence of the development subsystem and the operating system was minimized. The overall page/subpage structure used successfully in the first version was followed. Minimal changes were necessary in the ROV controller, which has always been hosted in a Linux system. The change to a Linux host for the GUI made it possible to reduce the processor count in the topside control van.

After many years of using the Windows-based DVLNav system for navigation, WHOI developed a client/server replacement that is used on many ROVs and AUVs (Howland et al., 2016). The server, or navigation engine, is called *navest*; it collects data from sensors and allows implementation of a variety of algorithms, including the dead reckoning algorithm used in ROV navigation. It supports the use of a variety of clients, including *navG*, which provides an operator interface to the sensors and algorithms, and allows a variety of map-based views or the operational environment. *navG* also supports the selective underlay of multiple digital map systems and collection and importation of targets (Figure 2).

The client/server model permits use of multiple copies and versions of *navG*, which can run on any Linux-based processor that can access data distributed over Ethernet by *navest*. This allows science users to have situational awareness displays that they can pan and zoom independent of the real-time display being manipulated by the ROV navigator. *navG* has been implemented in multiple locations in the control van, elsewhere on support vessels, and over telepresence systems.

The new software systems should support the OET vehicle family for the next decade. The adaptability of the new GUI should simplify enhancements to the vehicle and customization to OET-specific needs. Implementation of new algorithms in *navest* should foster research and enhance data quality. Furthermore, the resynchronization of OET software with current software in use elsewhere in the oceanographic community should enhance collaboration with other agencies and operators.

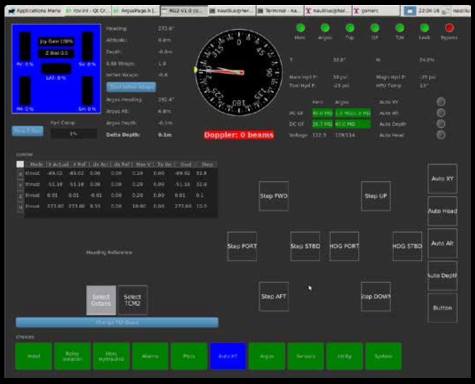



Figure 1. The ROV *Hercules* GUI, showing the Closed Loop Control page.

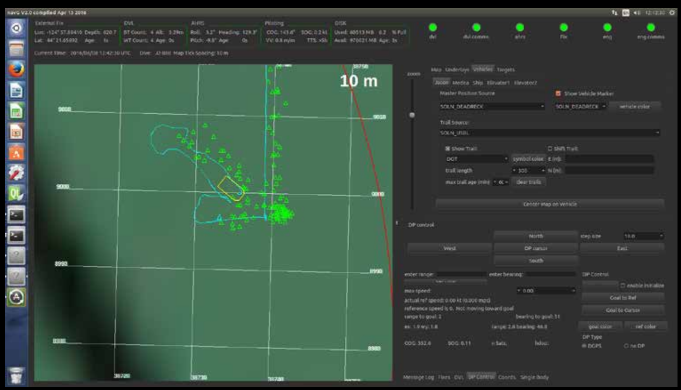



Figure 2. *navG* in use.



# *Nautilus* Samples 2016

## New Techniques and Partnerships

By Nicole Raineault, Jeffrey Marlow, Meredith Everett, Peter Etnoyer, Marie-Helene Cormier, Vanessa Knutson, and Gonzalo Giribet

In 2016, E/V *Nautilus* and the ROV *Hercules* collected 549 geological, biological, and water samples (2,022 subsamples) to characterize several US West Coast national marine sanctuaries, the Cascadia margin, and offshore southern California. Most samples are archived at partnering repositories: geological samples to the Marine Geological Samples Lab at the University of Rhode Island and biological samples to Harvard University's Museum of Comparative Zoology. The national marine sanctuary samples were split between these repositories and the California Academy of Sciences. During this field season, we experimented with new sampling methods to improve exploration efficiency and robustness.

### eDNA – (Meredith Everett)

Environmental DNA (eDNA) is genetic material obtained from an environmental sample rather than directly from an organism. Sampling of eDNA is noninvasive, easily detected, and cost-effective (Thomsen et al., 2015; Kelly et al., 2016; Valentini et al., 2016). The benefit of using ROVs to collect the water samples is the accompanying high-definition video of the coral species and its surrounding environment and also the ability to simultaneously collect voucher samples for initial characterization.

Over the course of the *Nautilus* 2016 field season, a total of 59 eDNA samples were obtained from habitats along the US West Coast, from the Cascadia margin to southern California. We used the technique for coral taxonomic identification in water samples and for microbes in sediment extracted from short push cores.

Water samples for use in eDNA analyses were taken in the vicinity of one or more deep-sea corals, with additional samples collected in the water column or away from corals to serve as negative controls. Environmental metadata and still images were collected for each sample. Each 1 L water sample was filtered on board the ship, and the filters were then placed in 5 mL of Longmire's lysis buffer for storage and transport. All samples were shipped back to NOAA's Northwest Fisheries Science Center, where eDNA was successfully extracted using methods similar to those in Kelly et al. (2016). Pilot sequencing using Illumina MiSeq Nano chemistry (2 × 250 bp) was successfully carried out on six samples using octocoral-specific primers, resulting in 864,991 sequence reads after filtering. Sequences from each sample were compared to a database of known coral species using GenBank and BLAST to sequence and identify the species observed in five out of the six samples (Figure 1). Additional work will be performed to optimize our methods and complete sequencing of all remaining samples.

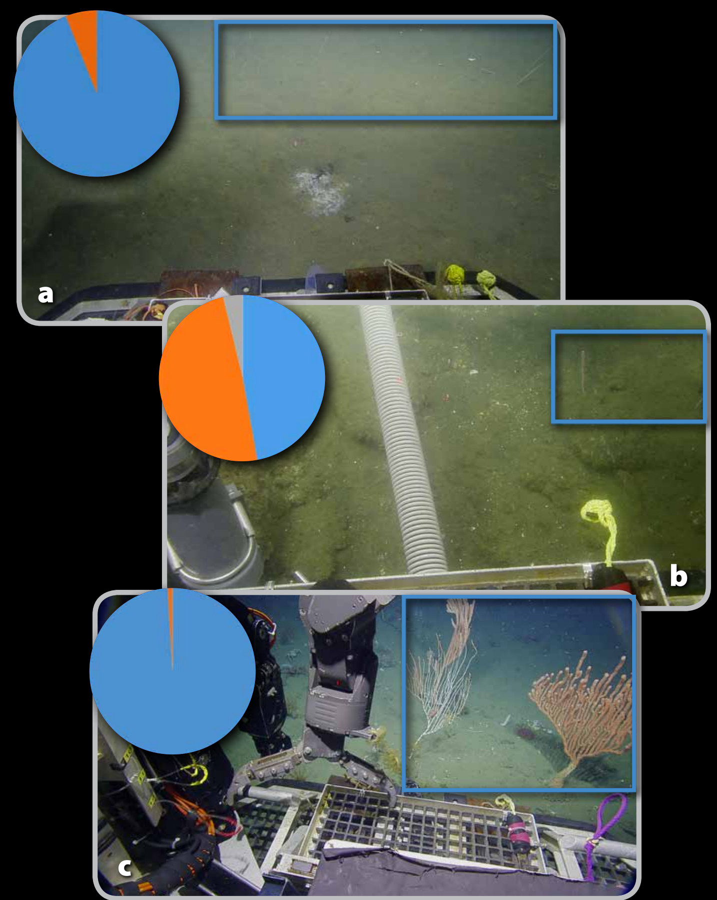



Figure 1. ROV *Hercules* images of three of the samples included in the pilot eDNA sequencing test. In each panel, the box surrounds the coral individuals that correspond to the sequences identified in the sample. The color of each box matches the colors in the charts. (a) *Halipteris* sp. individuals. In this sample, 93% of the sequences identified were from this species. (b) *Chromoplexaura marki* individuals. In this sample, 47% of sequences identified corresponded to this species, while 48% of sequences identified corresponded to *Plumarella superba*. (c) *Isidella tentaculum* individuals. In this sample, 99% of the sequences identified corresponded to *I. tentaculum*.

## Geochemical Sampling – Jeffrey Marlow

During the Central California cruise (pages 36–37), a streamlined suite of geochemical analyses was introduced to provide insight into subseafloor redox conditions, biological activity, and/or fluid flow. *Nautilus* is well established as a sampling platform for biological specimens, rocks, water, and sediment; incorporating minimally time-intensive geochemical analyses shipboard leveraged these samples and provided useful data to a wider range of researchers. Furthermore, as many of the geochemical species quantified are chemically reduced, prompt measurement upon collection was critical.

Water was collected from distinct depth horizons within sediment push cores from multiple dive sites. After pushing the fluid through a 0.2 µm filter, 0.5 mL aliquots were distributed to Eppendorf tubes for sulfide (mixed with 500 mM ZnAc), sulfate (6N HCl treatment, followed by 500 mM $BaCl_2$ solution), and ferrous iron (mixed with ferrozine solution) analyses. Additional filtered water (~5–8 mL) was placed in a 15 mL Falcon tube and frozen at −20°C to allow for downstream, user-initiated studies, including shore-based ion chromatography. Samples are archived at Harvard University's Museum of Comparative Zoology.

Figure 2. *Hercules* collects a push core of a bacterial mat and underlying sediment on the Point Dume seeps, offshore Malibu, California.

## Purple Orb – Vanessa Knutson and Gonzalo Giribet

In July 2016, *Nautilus* collected a mysterious purple orb off of the Channel Islands that captured the imagination of people globally (pages 38–39; Figure 3). As of February 2017, the video of its collection (https://youtu.be/pqyKrvk0aZo) has over 1.9 million views on YouTube and has the world speculating as to what this beautiful purple orb could be. The delicate orb was collected using the *Hercules* suction sampler and is now at Harvard University's Museum of Comparative Zoology, where we are working to identify and describe it. Initial shipboard photos showed the hallmark foot of a snail, but did not show an obvious shell (Figure 3b). Based on this observation, the orb was originally speculated to be a pleurobranch snail. Pleurobranchs have reduced shells that are covered by the mantle or lack a shell altogether. Upon further review of key snail identification features on shore, we now think that the purple orb belongs to another distantly related group of snails, the velutinids. Many velutinids also exhibit a reduced shell that can be fully or partially covered by the mantle. We are using modern techniques, including micro-computerized tomography (microCT) scanning and RNA sequencing, to describe this very likely new species of velutinid.



Figure 3. (a) Image of the purple orb in situ, and (b) in the *Nautilus* wet lab, where the foot is visible. Scale bars are 1 cm.

## Live Coral Studies and Surveys – Peter Etnoyer

A total of 16 octocoral colonies were collected alive from the Channel Islands National Marine Sanctuary and shipped in seawater to NOAA's National Centers for Coastal Ocean Science in Charleston, South Carolina, where they are maintained in cold-water aquaria (Figure 4). These living colonies are particularly useful for studies of coral biology, feeding, and stress tolerance. Maintenance of these living colonies also facilitates experiments by graduate students at Grice Marine Lab to learn how the colonies respond and adapt to changing ocean conditions, such as warming and hypoxia. E/V *Nautilus* and ROV *Hercules* pilots are well equipped for sampling corals, as demonstrated by this remarkable collaborative effort.

A total of 12 video transects were conducted over hard- and soft-bottom habitats in the Channel Islands National Marine Sanctuary. The transects were short 5–15 minute intervals, with 10 cm spaced lasers in frame for scale. The surveys showed that rockfish and octocorals were typically abundant on hard-bottom, low-relief ridge substrates. Densities of octocorals in the area are known to exceed the one colony per square meter threshold, which meets international criteria for coral garden habitat. This observation is important because the coral garden aggregations can be detected in backscatter imagery, and they occur outside of existing marine protected areas within the sanctuary boundaries.

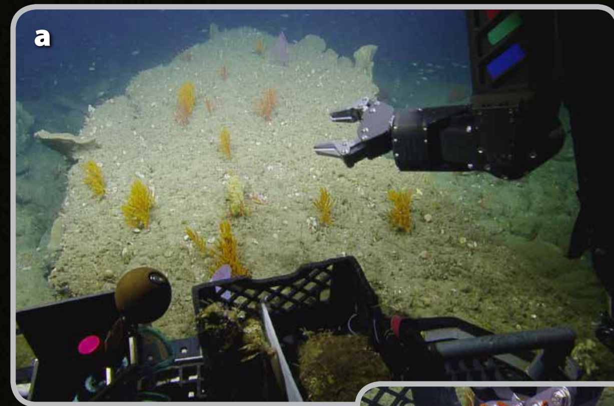



Figure 4. (a & b) Sea fan corals (*Adelogorgia* sp. and *Eugorgia* sp.) were collected by ROV *Hercules* from 50–100 m water depth in the Channel Islands and transported to (c) cold-water aquaria facilities at NOAA to study the effects of ocean warming.

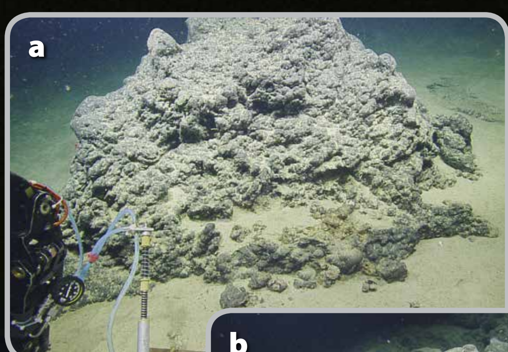
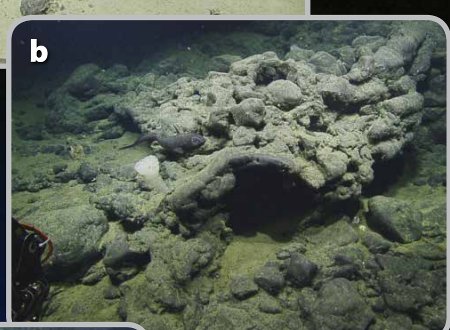
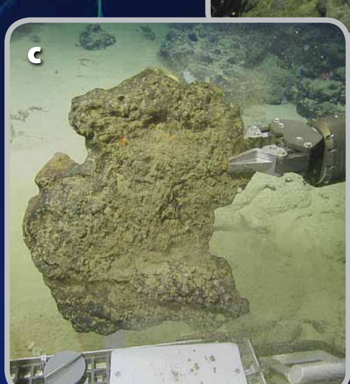




Figure 5. (a) A sample was collected from this intriguing mound, thought to be a fossilized cold seep, on Southwest Bank. (b) A sample from Patton Escarpment was originally thought to be a volcanic rock but instead has a thick manganese crust. (c) Sample atop Southwest Bank indicates a paleoshoreline at 556 m depth.

## Southern California Rock Samples – Marie-Helene Cormier

Many of the 2016 *Hercules* dives targeted sites of geological interest, including active fault zones and folded rock formations, volcanic seamounts and a guyot, canyons and shallow banks exposing ancient shorelines, and the steep, ~3 km high Patton Escarpment, a prominent feature that represents the trench slope of a fossil subduction zone. On the southern California margin cruise (pages 40–41), approximately 130 geological samples were collected, some of them offering surprising new insights. For example, preliminary inspection of a sample from Southwest Bank suggests that it may be from a fossilized cold seep sitting atop a previously unrecognized strike-slip fault (Figure 5a). Likewise, cursory inspection of a sample from Patton Escarpment revealed that the black, smooth outcrops observed across the escarpment represent an unexpectedly thick manganese crust, not lava flows as was initially postulated during the dive (Figure 5b). Additional geological samples from paleoshorelines (Figure 5c) and fault zones are awaiting analysis; it is anticipated that they will help constrain vertical motion and recent seismic activity offshore southern California.

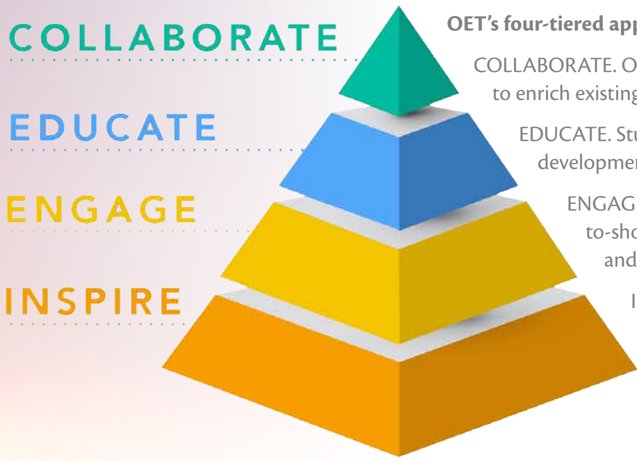
# Nautilus Education & Outreach Programs

## Igniting Interest and Promoting Literacy in Ocean Exploration and STEM Careers

By Allison Fundis, Megan Cook, Katherine Sutton, Scott Munro, Daniel Larsh, Kelly Moran, Alexandra Witten, Samantha Wishnak, and Susan Poulton

The need to increase interest and literacy in STEM fields among students and the broader public inspires the Ocean Exploration Trust to find new ways to share E/V *Nautilus* expeditions and discoveries with global audiences. Through a series of educational and outreach programs, OET connects people from a variety of settings—including classrooms, museums, science centers, community colleges, and universities, as well as living rooms—to sea-going explorers and their research. Through these programs, OET aims to contribute to public awareness and appreciation of the importance of ocean exploration and the diverse STEM vocations that make ocean exploration possible. Additionally, OET strives to better equip individuals in the next generation with the skills and role models they need to be our future explorers, innovators, policymakers, and members of a productive workforce.

OET uses research conducted aboard E/V *Nautilus*, the ship's associated technologies, and shore-based facilities at the University of Rhode Island's Inner Space Center to take a multifaceted approach to education and outreach. Programming includes (1) outreach to inspire the online public through 24/7 connectivity to explorers at sea; (2) ocean exploration-themed STEM curricular materials; (3) professional development opportunities for educators on shore; (4) infusion of *Nautilus* content into science centers, aquaria, museums, and other informal education institutions; (5) immersive, hands-on opportunities for students, educators, and artists to participate in E/V *Nautilus* expeditions; and (6) strategic partnerships that focus all of these programs in select communities across the United States. OET uses a four-tiered approach—inspire, engage, educate, collaborate—to its outreach and education programs, with each step and subsequent program building on the previous one, allowing a deeper level of learning and impactful experiences as learners progress.




**OET's four-tiered approach to education and outreach programs:**

COLLABORATE. OET works with partners and stakeholders within select communities to enrich existing programs through access to the Nautilus Exploration Program.

EDUCATE. Students and educators make use of educational and professional development opportunities and participate in *Nautilus* expeditions.

ENGAGE. Audiences engage with the Corps through public live ship-to-shore broadcasts, and in museums, science centers, public venues, and classrooms.

INSPIRE. Individuals are introduced to the *Nautilus* Corps of Exploration through digital media, television specials, and documentaries.

# TIER 1. INSPIRING THE PUBLIC

OET's outreach goals include introducing a broad and diverse global audience to the process of exploration and the excitement of discovery while continually adjusting to the rapidly changing landscape of digital and mass media. During the 2016 *Nautilus* field season, we continued to focus efforts on live streaming video of deep-sea exploration, using social media, and engaging news media in addition to experimenting with new ways to reach the public through evolving social platforms.

## NAUTILUS LIVE

The Nautilus Live website generated more than 2.7 million views and featured live streaming video of expedition operations through cameras on the ship and on the ROVs, accompanied by live audio commentary from scientists, engineers, educators, and students. Through the participatory question-and-answer feature embedded in the website, our team fielded approximately 55,000 questions from the public over the course of the four-month field season.

## SOCIAL MEDIA

Nautilus Live's Facebook audience increased more than 30% to over 79,000 followers, with an extended reach of more than 7.6 million. In early 2016, Facebook Live became widely available with the News Feed algorithm, placing emphasis on live broadcasts. This feature allowed OET to reach fans in the moment, as we were able to facilitate participatory conversations from *Nautilus* directly with our followers. Through our own Facebook Live streams and in partnership with The Weather Channel's Facebook Live team, we reached over half a million people. *Nautilus* expeditions also reached the coveted Top Trending status on Facebook twice during the 2016 field season for our widely circulated video of a "googly eyed" stubby squid and our exploration of the sunken WWII aircraft carrier USS *Independence*.

In addition to Facebook, we continued to grow our audience through Twitter, Instagram, and YouTube. On Twitter, @EVNautilus doubled its following with an extended reach of approximately 3.6 million impressions. Our Instagram and YouTube continued to serve as prominent outreach platforms to reach younger audiences, with traffic on Instagram increasing approximately 50% since 2015 and YouTube traffic up to over 28.7 million views. The ability of quality content to spur imagination and scientific curiosity attracted a diverse and active conversation across these platforms and continued to increase audience participation.

## PRESS AND MEDIA

The work of the scientists and explorers aboard *Nautilus* was featured in over 6,500 news reports in print, television, radio, and online, with an estimated reach of more than 400 million people. Media outlets included CNN, *Washington Post*, CBC, Fox News, Smithsonian, National Geographic, MSNBC, *The Guardian*, AP, Reuters, Huffington Post, CNET, PBS, Business Insider, and many others. Stories covered diverse topics, from exploration of methane seeps off the Oregon coast, to the discovery of a mysterious purple orb-like creature off of California, to the first visual exploration of a WWII aircraft carrier since it was scuttled near the Farallon Islands in 1951 after serving as a target in the Operation Crossroads atomic bomb tests. Scientists, partners, students, and educators participating in expeditions during the 2016 *Nautilus* field season were often featured in local and national media stories.


Winning entry and final design of the annual *Nautilus* expedition patch design contest submitted by Gustopher Miller from New York.

# TIER 2. ENGAGING SHORESIDE AUDIENCES

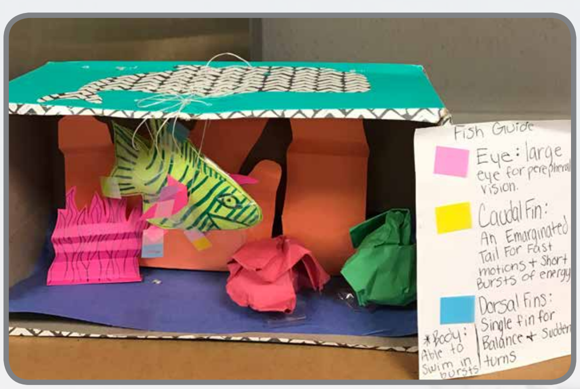
## LIVE SHIP-TO-SHORE INTERACTIONS

Through live ship-to-shore interactions, OET emphasizes the importance of role models, and highlights the varied opportunities and STEM-related careers available in ocean exploration, as well as the diversity of backgrounds of the participants in the Nautilus Exploration Program. During the 2016 field season, OET conducted 368 broadcasts to 112 locations in 20 states and four countries via telepresence technology installed on *Nautilus*. Through this program, guests at partner museums, aquaria, and science centers engage in a two-way conversation with members of the Corps of Exploration directly from *Nautilus* through facilitated shows at partner sites. Major partners during the 2016 field season included the Aquarium of the Pacific, Connecticut Science Center, Exploratorium, Houston Museum of Natural Science, Perot Museum of Nature and Science, Seacoast Science Center, Submarine Force Library & Museum, NOAA Office of National Marine Sanctuaries, and Titanic Belfast Museum. OET also continued outreach programs with a variety of schools, universities, out-of-school programs, and other venues.

Students at the Perot Museum of Nature and Science in Dallas, Texas, participate in a live ship-to-shore Q&A session with members of the Corps of Exploration aboard E/V *Nautilus*.

# TIER 3. EDUCATION PROGRAMS & RESOURCES

Since 2009, OET has established partnerships with schools, out-of-school programs, and informal educational institutions to develop and implement resources and programs that (1) inspire young audiences to be lifelong learners and pursue interests, education, and careers in STEM; (2) provide educators with engaging professional development opportunities and increase their capacity to use OET-produced curricular materials effectively; and (3) provide hands-on professional training and vocational development for students advancing through STEM-focused degrees and career exploration.




A student's final product after completing the "Any Fin is Possible" STEM Learning Module about fish adaptations in Lemont, Illinois.

## STEM LEARNING MODULES

OET's STEM Learning Modules are inquiry- and project-based lessons that supplement educators' curricula and foster student engagement in the STEM disciplines found in oceanographic research and exploration. Lessons lead students through fundamental concepts involved in deep-sea exploration such as pressure, density, and buoyancy; methods for mapping the seafloor; tectonic plate dynamics; fish adaptations; and engineering design. Each lesson includes guiding questions, standards addressed, educator and learner instructions, and universal assessment rubrics. The STEM Learning Module lessons are designed for sixth graders, with extensions for a variety of grade levels, student needs, and learning environments, and they are guided by the performance expectations of the Next Generation Science Standards, Common Core State Standards, and Ocean Literacy Principles.

Developed by professional educators within the Corps of Exploration, the first edition of nine STEM Learning Modules was published in June 2015. In 2016, this resource expanded to include 19 lessons that are supplemented by instructional videos to guide educators through setup and implementation of many of the lessons. The resources are currently available to the growing network of educators participating in OET's Community STEM Program, Science Communication Fellowship, and Nautilus Ambassador Program.

## PROFESSIONAL DEVELOPMENT WORKSHOPS

In parallel with the expansion of STEM Learning Modules, OET has continued to grow its professional development workshop effort for formal and informal educators in partner communities. Attending educators receive the full suite of STEM Learning Modules, hands-on training with the module activities, best practices for incorporating live deep-sea exploration into instruction, and the opportunity to network with local educators and STEM professionals. These workshops highlight foundational STEM concepts in ocean exploration and train educators in identifying linkages to their current curricula and programming. Participants also have the opportunity to link their learners to role models within the Corps of Exploration through telepresence-enabled ship-to-shore interactions.

In 2016, OET hosted professional development workshops for educators in California, Texas, Louisiana, New Hampshire, Illinois, and Connecticut. These workshops provided training for 138 educators from classrooms, museums, aquaria, after-school programs, universities, and education nonprofits, with a combined reach of over 57,000 learners.

## HONORS RESEARCH PROGRAM

Since 2010, the Honors Research Program has provided the opportunity for rising high school seniors to participate in a summer program for several weeks at the University of Rhode Island Graduate School of Oceanography, after which they are part of the science team on board *Nautilus*. While at the Graduate School of Oceanography, students are exposed to the interdisciplinary nature of oceanography by experts in geology, biology, archaeology, engineering, science communication, and computer science. Students collaborate on STEM projects aimed at preparing them for their time at sea and contributing research data to the scientific community.

This season, eight students participated from public, private, and charter high schools in California, Colorado, Illinois, Ohio, Virginia, and Washington. Students collaborated on the design, construction, sampling proposal, and deployment of two GPS-enabled surface ocean drifters to study the complexities of global ocean currents. Collaborating with local scientists and using global models, students selected launch points for the drifters along the California coast. The drifters collected data for 43 and 81 days. The data were shared with industry partner Remote Sensing Inc., who uses the information to refine computer models of California coastal currents. Student data were also featured on the NOAA Northeast Fisheries Science Center website.

## SCIENCE & ENGINEERING INTERNSHIP PROGRAM

Since 2009, OET's Science & Engineering Internship Program has provided hundreds of talented undergraduates, graduate students, and early career professionals with on-the-job vocational training in the fields of ROV and video engineering, navigation, ocean science, and seafloor mapping while being mentored by professionals in each field. Interns, who are selected through a competitive application process, sail on *Nautilus* for three to five weeks as part of the expedition team. ROV engineering interns learn about vehicle systems, maintenance, and operations in addition to filling the copilot role during ROV dives. Video engineering interns operate all video equipment during ROV dives and learn about the complexities that allow shipboard broadcast systems to stream live video and data to shore. Navigation interns focus on the logistics and operational skills required to work with ROVs and their support vessels. Ocean science and seafloor mapping interns work in key roles of the science team, including ROV dive annotation, data processing, sample management, and multibeam mapping surveys. All participating interns also serve as role models to their peers ashore and to learners around the world through the Nautilus Live website and live broadcasts from sea. In 2016, 14 students from nine states participated in this program. This cohort included student representatives from partnering agencies and institutions, including NOAA's Educational Partnership Program, US Naval Academy, and US Coast Guard Academy.

ROV Intern Jordan Caress conducts pre-dive checks on ROV *Hercules*.

Honors Research Program students Emily Vierling, Leslie Carrillo-Lorenzon, Kendra Pew, and Crista Kiely are ready to deploy their ocean current drifter from E/V *Nautilus*.

## NAUTILUS AMBASSADOR PROGRAM

The Nautilus Ambassador Program brings invited educators from our Community STEM Program sites to sea on board *Nautilus* to participate in ocean exploration while the ship transits between cruise sites. In 2016, the Nautilus Ambassador Program brought six middle and high school educators from Community STEM Program locations funded by CITGO aboard a three-day transit off California. During their time on board, the educators observed an ROV dive, gained experience in life aboard a research vessel, processed samples in the wet lab, and built a portable and low-cost ROV with OET partners from OpenROV. The educators also conducted live ship-to-shore interactions with students and community members in their home states of Texas, Illinois, and Louisiana.

After returning home from their at-sea experience, Nautilus Ambassadors continue their involvement by conducting local outreach within their communities and serving as mentors to other educators working with OET's education resources. The Nautilus Ambassador Program facilitates peer-to-peer educator engagement and empowers participants as leaders and community-based experts for their institutions.

Nautilus Ambassadors Shawn Gregg (Texas) and Sarah Steinke (Illinois) help process biological samples in the lab aboard *Nautilus*.

## SCIENCE COMMUNICATION FELLOWSHIP

The Science Communication Fellowship provides educators with the tools and training in the fields of science communication and digital storytelling, and introduces each participant to ocean exploration and STEM professionals working in the field. During the year-long fellowship, participants attend OET's annual Science Communication Workshop in Rhode Island to (1) learn effective science communication strategies and hands-on technical skills to enable them to translate their at-sea experience to shoreside audiences, (2) gain fundamental science and engineering knowledge to underscore the mission and objectives of the upcoming field season, (3) learn best practices for incorporating the Nautilus Exploration Program into formal and informal education spaces, and (4) bring personal experience and resources to network with other fellows and develop local outreach and education plans for the upcoming field season.

While at sea, Science Communication Fellows moderate the control room broadcast during live exploration, translating complex exploration science for global audiences and engaging the active online audience by weaving shore-based questions submitted through the website into the conversation. Fellows also lead the live ship-to-shore broadcast interactions with public venues and classrooms worldwide. Within their communities, they become role models of exploration and STEM outreach. The deliverable of the fellowship is a body of outreach or original STEM-focused lessons that translate the fellows' experiences to a broad audience of learners. These deliverables contribute to the growth and expansion of the STEM Learning Modules and resources that are made available to OET's expanding network of educators, partners, and program participants.

The 2016 cohort, selected through a competitive process, included 17 educators from nine states—Arkansas, California, Florida, Louisiana, Michigan, New Hampshire, New Jersey, Texas, Washington—as well as Australia. Fellows represented formal educational institutions from the elementary to the collegiate level, and encompassed public, private, and charter schools. Informal educators came from backgrounds as diverse as outdoor education, municipal and national museums, science centers, aquaria, and national programs.

The 2016 Science Communication Fellowship cohort and members of the Corps of Exploration attend OET's annual Science Communication Workshop.

# TIER 4. COLLABORATIONS & PARTNERSHIPS

## COMMUNITY STEM PROGRAM

With support from partnering universities, organizations, and corporations, OET's Community STEM Program aims to foster intracommunity collaborations through the lens of ocean exploration and STEM education. OET works with partners and stakeholders within participating communities—school districts, nonprofits, STEM professionals, public venues, and individuals—to infuse various elements of the Nautilus Exploration Program's educational opportunities and resources into local organizations and schools in order to nurture a deep sense of community and connection.

In 2016, the Community STEM Program was represented by three undergraduates participating in the Science & Engineering Internship Program, eight educators in the Science Communication Fellowship, five educators in the Nautilus Ambassador Program, and four high school students in the Honors Research Program. These individuals continue to use their experiences with and connections to the Corps of Exploration to promote STEM education and ocean exploration within their own communities. They have been active role models at professional conferences and public workshops, and they serve as mentors to their peers and younger students. Within our larger program, Community STEM Program professional development workshops reached over 57,000 learners. During our four-month expedition, 139 live ship-to-shore interactions were hosted for audiences in Community STEM Program locations in collaboration with our partners. The networks that have been established over the three years this program has been active have fostered strong connections among participants and have continued to provide momentum and to maintain focus on STEM careers and ocean exploration.

Participating communities in 2016 included Corpus Christi, Dallas, and Houston, Texas; Lake Charles, Louisiana; Lemont, Illinois; New London, Connecticut; Washington, DC; New Hampshire; and San Pedro, Santa Barbara, and San Francisco, California. Programs and program participants in each of these locations were supported with funding from our Community STEM Program partners—CITGO, Office of Naval Research, University of New Hampshire, AltaSea, Lyda Hill Foundation, University of California, Santa Barbara— and through private donations.

By igniting interest in ocean exploration and STEM careers, we hope to motivate more students and the public to be lifelong learners and to gain exposure to opportunities and careers of which they may not otherwise have knowledge. It is our goal to use all of our education program and outreach efforts to inspire our future explorers, innovators, and policymakers, as well as the STEM workforce, while ensuring that anyone can find a role model within the *Nautilus* Corps of Exploration.

Science Communication Fellow and McNeese University Assistant Professor Amber Hale talks about her *Nautilus* experience with students in Lake Charles, Louisiana.

Students visit and tour E/V *Nautilus* while in port at AltaSea in San Pedro, California.

# *Nautilus* Field Season Overview

By Katherine L.C. Bell, Nicole Raineault, and Robert D. Ballard

After coming online in the summer of 2009, E/V *Nautilus* spent its initial four years working in the Mediterranean, Aegean, and Black Seas. During that time, she frequented shipyards in Turkey to transform an outdated East German hydrographic ship, R/V *Alexander von Humboldt*, into a modern ship of exploration. One of the largest improvements was the installation of a Kongsberg EM302 multibeam sonar system, which underwent its field trials in the Mediterranean and during *Nautilus*' crossing of the North Atlantic in the spring of 2013. Each year, as more improvements were made to the ship, its Corps of Exploration took on more challenging missions.

Responding to requests from the oceanographic community through our Workshops on Telepresence-enabled Exploration, *Nautilus* spent the next two and a half years in the Caribbean Sea and the Gulf of Mexico before entering the Pacific Ocean for the first time in 2015. That same year, *Nautilus* settled into a home port at a new and growing marine campus called AltaSea in San Pedro, California.

From May to September 2016, following mobilization and a shakedown cruise off the coast of Victoria, British Columbia, *Nautilus* continued its mission of exploration, innovation, and education in the eastern Pacific Ocean, covering the west coasts of southern Canada and the United States. Over the course of the four-month expedition, nearly 300 participants from more than 100 organizations sailed on board and participated on shore.

ROV *Hercules* surveying mudstone concretions discovered off Santa Barbara Island.

The first cruise of the year, led by Ocean Networks Canada, involved a complex, two-vessel operation with the cable ship *Wave Venture* to install and repair equipment at some of the NEPTUNE observatory's deepest sites (pages 26–27).

Following our work in Canada, we spent nearly three weeks in June exploring the Cascadia Margin. One of the first dives was just over the Canada-US border, where we set eyes on the S/S *Coast Trader* for the first time since the freighter was sunk by the Japanese submarine *I-26* in 1942 (page 31). The wreck was inspected to study the potential pollution threat of the oil held within the vessel. The Cascadia margin cruise then continued south, from Washington to northern California (pages 28–30). A collaboration with the NOAA Pacific Marine Environmental Laboratory, this cruise mapped a considerable amount of area ranging between ~125 and 3,000 m water depth, and we located more than 500 water column anomalies within the same region. Several ROV dives targeted the anomalies and characterized 10 previously undiscovered cold seep sites on the seafloor, including carbonate deposits, clam beds, and methane hydrates. During this cruise, we also dove in Quinault Canyon, within the Olympic Coast National Marine Sanctuary, to ground truth a sonar survey that had been completed earlier in the year.

The Central California cruise was meant to explore from San Francisco to Los Angeles, but due to inclement weather, *Nautilus* was forced to remain on the southern end of the operating area, south of Point Conception (pages 36–37). Much of the mapping and ROV dives were undertaken in Santa Barbara Basin, as well as at a seep site on Point Dume that was discovered in 2015. We also dove on the southeast side of San Juan Seamount, a large, under-explored seamount in the outer borderland. Biological and geological samples were collected to better understand the relationship between this enigmatic feature and its surroundings.

### 2016 *Nautilus* Field Season at a Glance

| | |
|---|---|
| 9 | Cruises |
| 130 | Days |
| 88 | ROV dives |
| 804 | Hours in the water (33.5 days) |
| 549 | Samples collected (2,259 subsamples) |
| 39,445 | Square kilometers mapped |

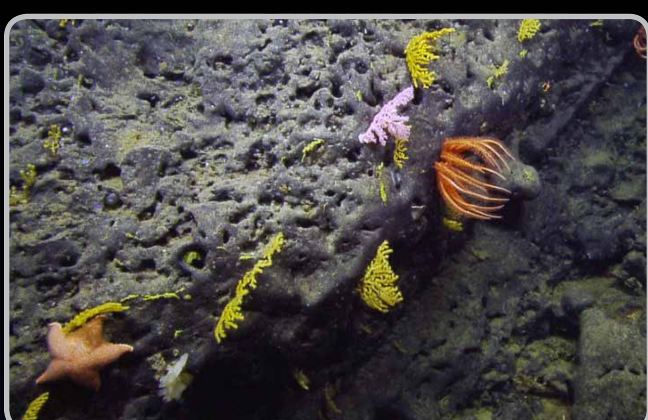
In July, we collaborated with the Channel Islands National Marine Sanctuary to embark on two cruises—one to map large areas of the sanctuary, and one to dive on targets identified during the mapping cruise (pages 38–39). We mapped nearly 2,500 km$^2$ of seafloor and conducted 10 ROV dives, many of which were planned in collaboration with several Scientists Ashore who participated in the cruise via telepresence. In addition to biological and geological exploration of the Channel Islands, we also experimented with new sampling techniques and technologies, which we hope to continue deploying aboard ROV *Hercules* for enhanced sample collection (pages 15–17).

*Nautilus* continued pushing south, exploring the Southern California Borderland in late July and early August (pages 40–41). The targets of this cruise were primarily geological in nature, including submerged marine terraces, fault zones, and seamounts. Throughout the cruise, we discovered new cold seeps and four whale falls, and made observations about biological communities. We also worked with the MIT Media Lab to deploy exciting new tools for deep-sea virtual reality, data sharing and visualization, and marine habitat restoration (pages 12–13).

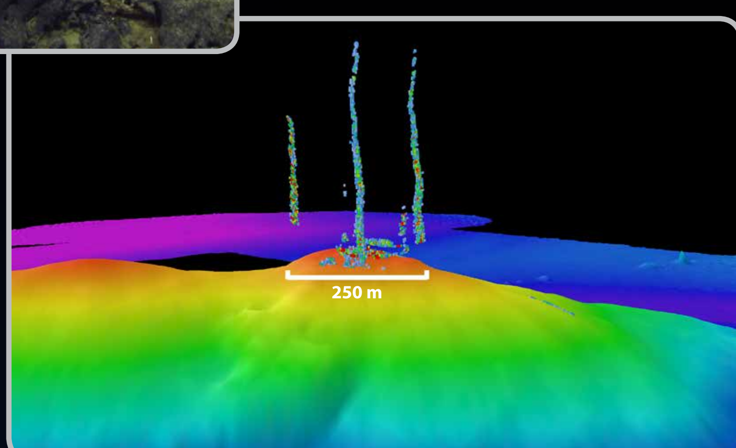
The final ROV cruise was undertaken in the Greater Farallones and Monterey Bay National Marine Sanctuaries (pages 32–33). A large focus was on USS *Independence*, which had been imaged with sonar previously but not seen since the aircraft carrier was sunk in 1951 (pages 34–35). We completed photographic mapping and 40 hours of detailed video surveys to study the state of the wreck, its radioactivity levels, and its role as marine habitat for the sanctuary. The remainder of the cruise was spent exploring the biological and geological aspects of the Greater Farallones sanctuary, including seafloor mapping and several ROV dives, as well as exploring S/S *Dorothy Wintermote* and S/S *Ituna*. Following the Greater Farallones cruise, *Nautilus* continued its seafloor mapping from the Cascadia Margin to southern California.

Given that the Pacific Ocean covers almost one-third of Earth's total surface area, including its deepest depths, it will be quite some time before this great ocean is thoroughly explored. In response to this challenge, the Ocean Exploration Trust is currently building a new mobile exploration capability much like the one it had before *Nautilus* came online. The system will be constructed in its new 20,000 square foot facility at AltaSea, in close proximity to the Port of Los Angeles. Having both *Nautilus* and this new mobile capability will make it possible for our Corps of Exploration to respond in a cost-effective manner to the growing requests around the globe that our workshop process continues to generate, taking us to the distal limits of this vast ocean basin.

Honors Research students Leslie Carrillo-Lorenzo and Emily Vierling solder parts of an OpenROV aboard *Nautilus.*



Coral and benthic fauna were observed at San Juan Seamount.




Several large anomalies rise into the water column above an accretionary ridge on the southern Cascadia margin. View is looking east/northeast and is two times vertically exaggerated.

# *Wiring the Abyss* 2016: Ocean Networks Canada's Most Challenging Expedition

By Kate Moran, Adrian Round, Ian Kulin, and Richard Dewey

Ocean Networks Canada (ONC) undertook the most challenging expedition in its 10-year history, from May 10 to May 29, 2016, in the Northeast Pacific Ocean. This complex two-ship expedition successfully installed a 6.5 tonne node and four sections totaling 18 km of steel-armored fiber-optic cable at some of the NEPTUNE observatory's deepest and most volatile sites. Real-time streaming video and social media postings engaged viewers from around the world by highlighting critical discussions among ship captains, dive chiefs, ROV teams, scientists, and science communicators and by allowing them to dive with the ROVs without getting wet.

The 142 m cable ship *Wave Venture*, operated by Global Marine Systems, was used to deploy the heavy node and cable. E/V *Nautilus* and its ROVs *Hercules* and *Argus* were employed to connect cables, install instruments, sample critical habitats, map the seafloor, and prepare for future installations from US research vessel *Sikuliaq* in June 2016.

The Barkley Canyon node, which was damaged by a trawler in January 2015, was redesigned and redeployed, bringing vital instrumentation back online. One of the instruments redesigned and deployed from *Nautilus* was Wally, ONC's Internet-controlled seafloor crawler. The German Center of Artificial Intelligence equipped Wally with a new laser imaging system to perform scans of the seafloor and hydrate mounds to 1 mm resolution.

Figure 1 (right). This beautiful wide-eyed octopus was spotted during an ROV dive to the Endeavour Ridge hydrothermal vent area.

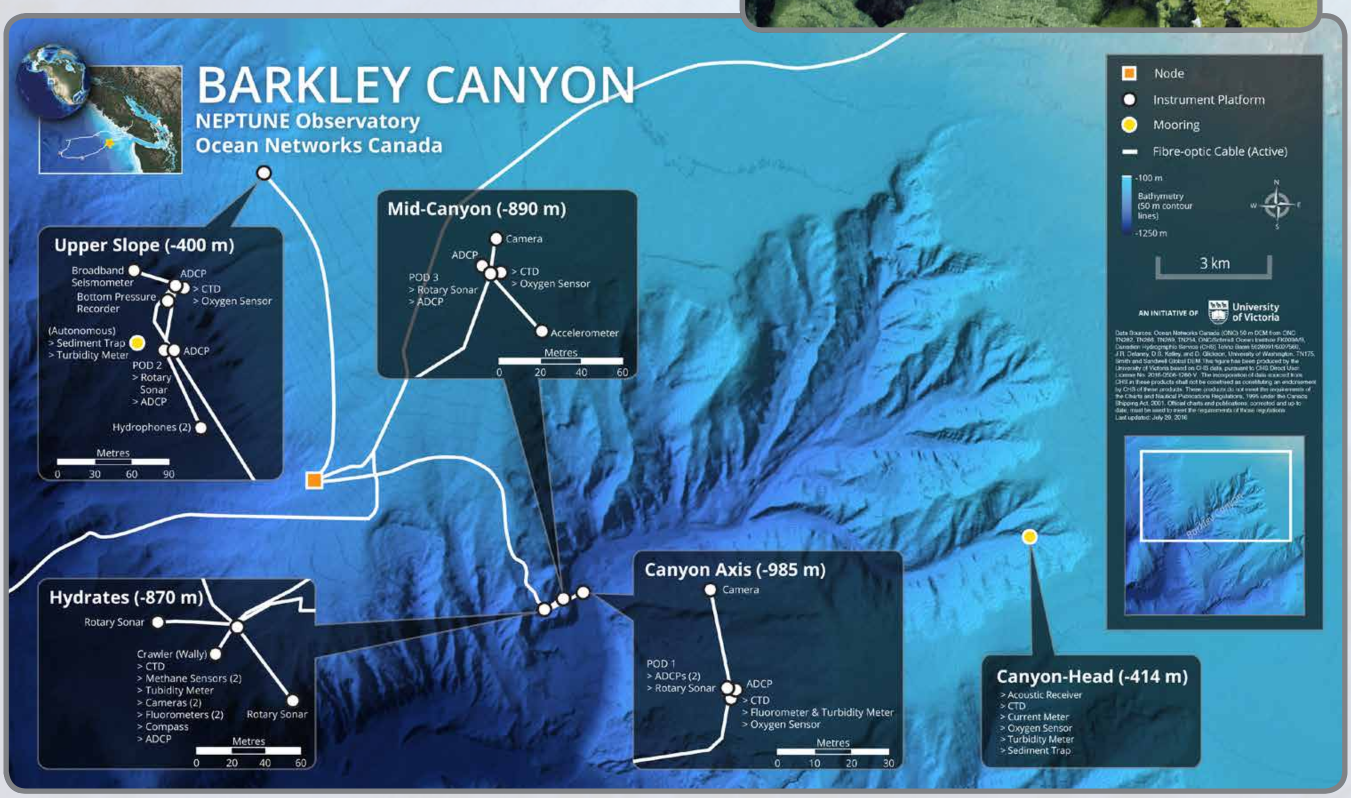



Figure 2 (above). Barkley Canyon extends from the continental shelf edge (400 m) down to the continental slope at the canyon axis (985 m) and supports studies of gas hydrates, sediment dynamics, upwelling, plankton, and productivity.

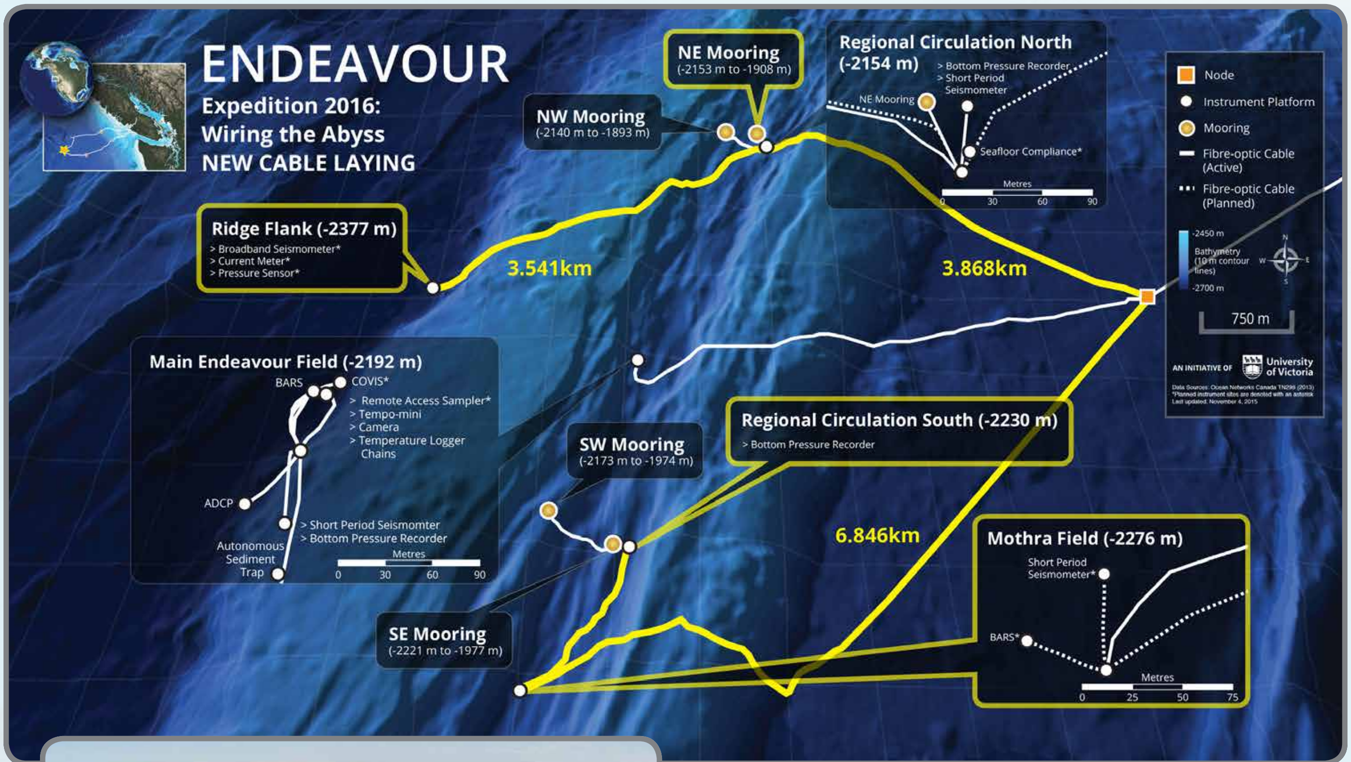



Figure 3 (above). Three new cable extensions bring power and communications to Endeavour Ridge, south to Mothra (the largest venting site at Endeavour), and west across the seafloor spreading zone to the Pacific Plate. A fourth cable at Clayoquot node to CORK1364A (an instrumented borehole) will allow the connection of a Woods Hole Oceanographic Institution tiltmeter in 2017.

Figure 4 (left). A drone perspective dwarfs the 142 m cable ship *Wave Venture*, anchored behind the 64 m E/V *Nautilus*.

Secondary cables laid during this complex expedition will serve new installations of earthquake early warning sensors and seismometers on the Pacific, Juan de Fuca, and North American Plates. A new cable was also laid in preparation for the installation of a Woods Hole Oceanographic Institution tiltmeter to monitor and study slowly slipping plate movements similar to those that preceded the Japanese earthquake and tsunami in 2011.

ONC worked closely with TE Subcom and Global Marine Systems to provide a dependable approach to secondary cable installations. Cables supplied by TE Subcom were laid point to point with heavy structures called mud mats on each end, using a technique developed by TE Subcom. This deployment was a first for Global Marine in an adaptation of the company's intercontinental cable laying expertise.

To complete these operations, *Wave Venture* and *Nautilus* worked in tandem, at times as close as 100 m apart. *Wave Venture* paid out the cable from its stern to depths as great as 2,600 m. Meanwhile, ROVs *Hercules* and *Argus* were deployed so that the *Nautilus* team could observe cable contact with the seafloor from the control room and direct the ROVs to manipulate the cables in order to avoid loops, kinks, or chafe points that could compromise the integrity of the cable.

An innovative technique—using communication over power lines—successfully brought bottom pressure recorder data online at ONC's Cascadia Basin tsunami array. The ability to assimilate open-ocean data from the cabled observatory into an operational tsunami forecast model makes it possible to provide updated wave arrival time and inundation information. This could help mitigate the impact of future tsunamis approaching the west coast of North America.

The 2016 *Wiring the Abyss* expedition significantly expanded the footprint and research capacity of Canada's national ocean observatory. A University of Victoria initiative, ONC manages the world's most advanced cabled ocean observatories off the west coast of Canada and in the Arctic for the advancement of science and the benefit of Canada. Research areas include climate change and its impact on gas hydrates, earthquakes, and tsunamis; life in extreme environments; and the impact of hot vent fluids on ocean chemistry and circulation.

# Water Column and Cold Seep Exploration of the Cascadia Margin

By Robert Embley, Nicole Raineault, Susan Merle, Tamara Baumberger, Sarah Seabrook, and Stephen Hammond

In 2016, the primary focus of E/V *Nautilus* exploration along the US-Cascadia continental margin from the Strait of Juan de Fuca to Cape Mendocino was to map bubble streams, sample methane seeps, and observe seep habitats (Figure 1). Bubble streams are defined as vertically oriented coherent water column sonar returns that originate at the seafloor. Although many of the classic studies of methane cold seeps and methane hydrates have been conducted along this accretionary margin (Johnson et al., 2015), prior to 2016, the distribution of methane seeps was largely unknown, with many areas and depth ranges not yet explored.

During the 2016 field season, sonar surveys conducted during cruises NA072 and NA078 located more than 500 water column bubble streams from 125 m to 1,630 m water depth, and the ROV dives during NA072 characterized 10 cold seep seafloor sites (Figure 1).

Most of the time along the Washington margin was devoted to ROV dives in non-seep areas to explore and map seafloor habitats, but some shipboard sonar surveys were conducted on the northernmost portion and along the transits between dives. New bubble streams were discovered and dives were made at two seep sites on the upper slope near Juan de Fuca Canyon (845 m water depth) and on the shelf in that region (~135 m water depth). On the northern Oregon margin, new bubble streams were discovered within and near the head of Astoria Canyon (Figure 2), along several swaths across the accretionary wedge as deep as 1,630 m, and in shallow water around Nehalem Bank. Two dives characterized sites on the canyon floor where methane hydrate was exposed and on the canyon's south wall at ~500 m depth where extensive methane bubble flux, carbonate, and seep fauna were observed. At Nehalem Bank, we observed an extensive mixed fishery and seep habitat. The transit from Astoria Canyon to southern Coquille Bank along the 500 m bathymetric contour followed the approximate shallow limit of the hydrate stability zone along the Cascadia margin. Historic data located a number

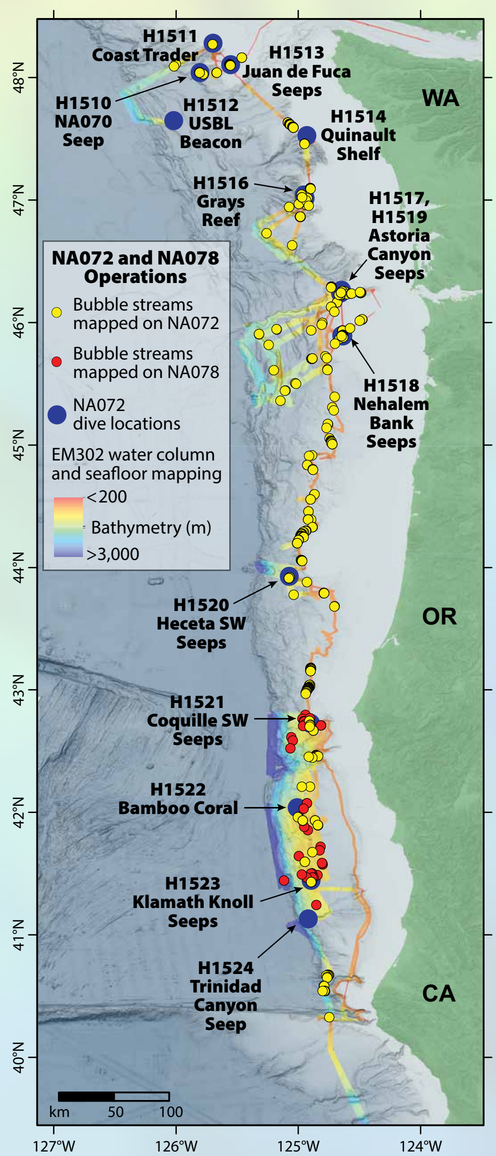
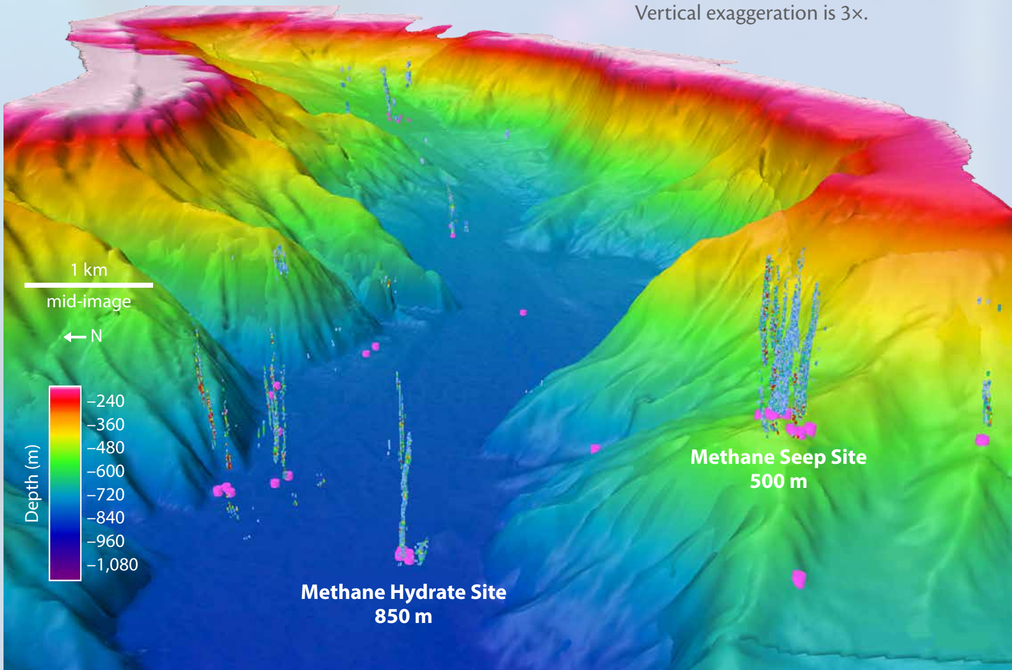



Figure 1 (left). Bathymetry tracks collected during cruises NA072 and NA078 on the US Cascadia margin, overlaid with bubble stream and ROV dive locations. More than 500 bubble streams were discovered here during the *Nautilus* 2016 field season. *Background grid credit: Chris Goldfinger, Oregon State University*

Figure 2 (below). Three-dimensional view of the head of Astoria canyon. Magenta cylinders are bubble stream locations on the seafloor. Vigorous bubble streams are represented by three-dimensional point cluster objects, created using the Fledermaus FMMidwater module©. ROV *Hercules* dives H1517 and H1519 visited sites on the middle of the canyon floor and on the south wall. Vertical exaggeration is 3×.



## Olympic Coast National Marine Sanctuary Exploration

The ROV *Hercules* dive on the Quinault Canyon rim supported Olympic Coast National Marine Sanctuary long-term goals of mapping and characterizing seafloor habitats and biological communities of the sanctuary. The head of Quinault Canyon is the deepest point in the sanctuary at over 1,400 m. Prior to 2016, the area had never been explored with modern technologies. In May 2016, NOAA's Office of Coast Survey completed a survey that provided sonar data suitable for habitat characterization and defined targets for further exploration. Weeks later, *Nautilus* provided the first images of the seafloor from the area and information for accurate surface substrate characterization. With six target areas defined, ROV *Hercules* was launched at the southernmost target site (see photos) and progressed northward to cover as much ground as time allowed. On visual inspection, high-reflectance areas were found to be late Pleistocene (>10,000 years old) gravels of glacial origin partially buried by younger Holocene sediments. The area east of the gravel deposits was identified as the northern extent of the Mid-Shelf Silt Deposit originating from the Columbia River. Visual observations provided initial characterization of epibenthic (living on or just above the seafloor) invertebrate and fish communities, identified locations of biogenic habitats (corals and sponges), and showed species-habitat associations.

## Sponge and Coral Habitat Assessment

The Grays Canyon Sponge Area was explored to further define species composition and underlying geology. This area had been previously explored using an autonomous underwater vehicle, but no samples were collected to allow specific identifications of sponges. In addition, there was a need to determine the underlying geology of the area so that it could be compared to similar sites described in Canada and Alaska. Video surveys were conducted at Grays Reef, and samples of the three predominant sponge species in the area were collected for expert identification (b). Subbottom profiles were collected and are being analyzed to determine the substrate on which these sponge "gardens" lie.

Several accretionary ridges on the Cascadia margin of southernmost Oregon and northern California have been identified where trawl surveys collected a large number of bamboo corals (c). These areas were mapped during NA072 and NA078, and one dive documented the bamboo corals' very high densities and good condition. Samples were collected to determine the ages of these delicate and beautiful corals.




ROV *Hercules* seafloor photos of: (a) rock fish in Quinault Canyon, Olympic Coast National Marine Sanctuary, (b) glass sponge in Grays Reef, and (c) bamboo coral found on accretionary ridges.

of sites along both the Washington and northern Oregon margins near this isobath (Johnson et al., 2015), and many new sites were found at or near this depth between Astoria Canyon and southern Heceta Bank. An excursion into deep water was made southwest of Heceta Bank, where we discovered several major bubble streams at ~1,230 m depth. Within a ~1 km$^2$ area, we discovered an extensive area of carbonate deposits, clam beds, tubeworms, and other seep fauna, as well as a small exposure of methane hydrate. Only a few sites were found on the transit along the 500 m contour between southern Heceta Bank and northern Coquille Bank, and no excursions into deep water were made in this region.

The area from the southern half of Coquille Bank to Trinidad Canyon had numerous bubble streams at depths ranging from 450 m to 1,625 m. Many of the sites were on accretionary ridges. Two seep dives were made in this region, southwest of Coquille Bank (615 m) and Klamath Knoll (part of an accretionary ridge, 730 m). The NA078 survey later completed examination of a large block of mixed canyon and ridge terrain in this region (Figure 1), revealing many new bubble streams. Although no bubble streams were detected within the deeper, surveyed portion of Trinidad Canyon, a small seep was discovered on the north wall of the canyon at 2,180 m depth.

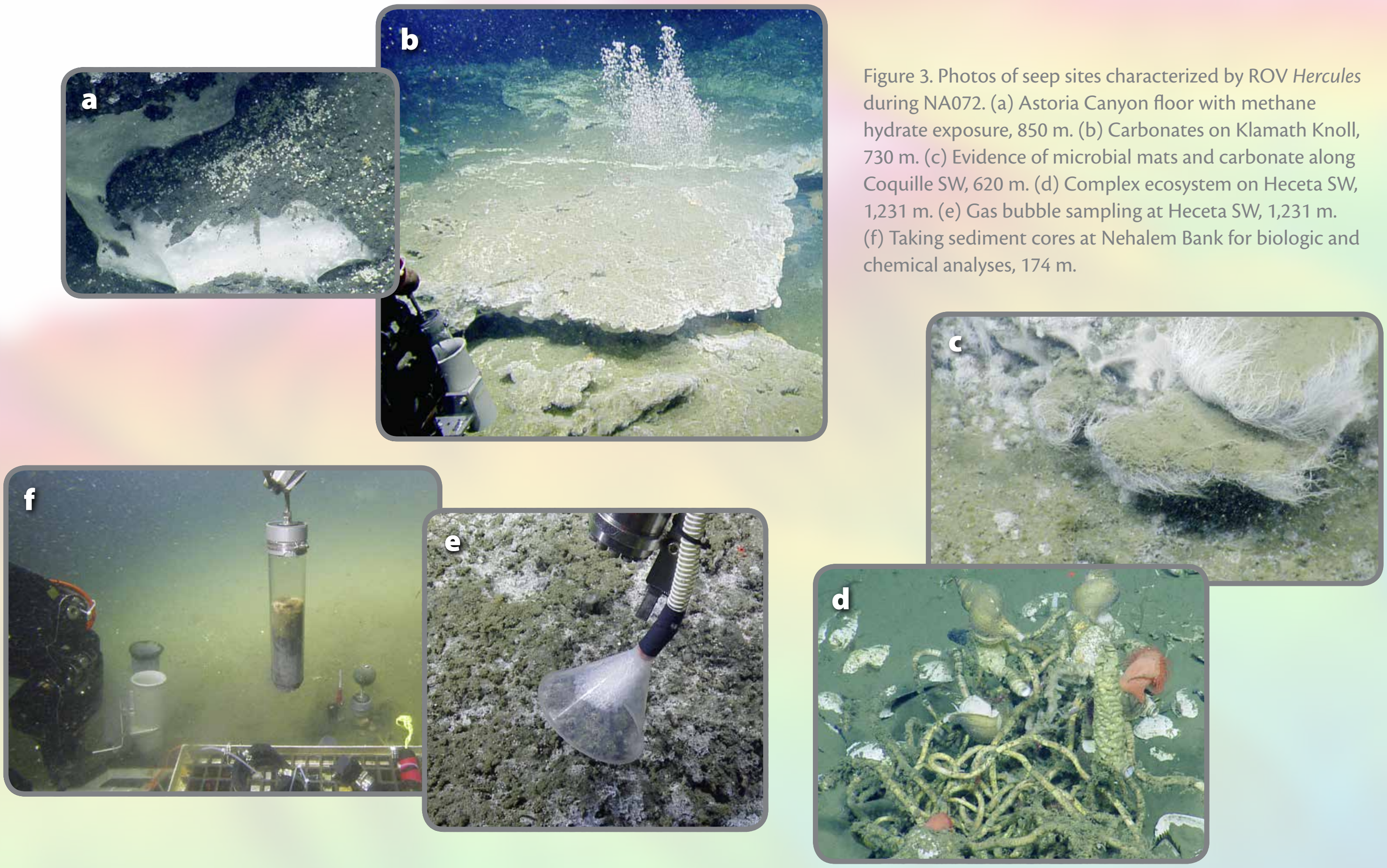



Figure 3. Photos of seep sites characterized by ROV *Hercules* during NA072. (a) Astoria Canyon floor with methane hydrate exposure, 850 m. (b) Carbonates on Klamath Knoll, 730 m. (c) Evidence of microbial mats and carbonate along Coquille SW, 620 m. (d) Complex ecosystem on Heceta SW, 1,231 m. (e) Gas bubble sampling at Heceta SW, 1,231 m. (f) Taking sediment cores at Nehalem Bank for biologic and chemical analyses, 174 m.

## ROV Dives and Observations

In addition to seafloor and water column mapping, we also characterized new and varied seep sites, including: (1) shallow sites on the continental shelf at Juan de Fuca Canyon and Nehalem Bank; (2) sites with methane hydrate exposed on the seafloor of Astoria Canyon and Heceta SW (Figure 3a); (3) extensive carbonate exposures on Astoria Canyon's southwest wall, Heceta SW, Coquille SW, and Klamath Knoll (Figure 3b,c); (4) extensive and complex seep ecosystems, for example, in Astoria Canyon, Heceta SW (Figure 3d), Klamath Knoll, and Coquille SW; and (5) evidence for storage of and periodic release of methane from subsurface carbonate cavities at Coquille SW and Klamath Knoll (Figure 3b,c). These sites were explored visually, and a range of samples were collected at the seep sites, including bubble streams at the seafloor interface using gas-tight bottles (Figure 3e), sediment cores for biologic and chemical analyses (Figure 3f), carbonates, and macrofauna.

At Heceta SW and Coquille SW seeps, a small autonomous hydrophone was deployed during the dives near bubble stream sources with the goal of relating bubble formation to methane flux rates. Initial results indicate that we succeeded in recording acoustic signals created by the formation of bubbles at the seafloor interface. There was also an overarching coral sampling and identification program on this cruise, which is discussed in the sampling article (see pages 15–17).

## Concluding Remarks

*Nautilus* cruises NA072 and NA078 expanded the database for bubble streams and seep sites on the US Cascadia continental margin by a factor of more than two. New bubble streams were discovered in water depths from 125 m on the continental shelf to 1,630 m in the mid-slope region. This deeper depth limit is consistent with the 2,000 m limit for bubble streams indicated by Johnson et al. (2015). The 2016 water column surveys only covered ~18% of the US Cascadia margin (that extends from the Canadian/US maritime boundary to Cape Mendocino) from 100 m to the base of the slope, so there are likely many more sites to be discovered here. We envision, with a modest amount of additional survey time, completing sonar surveys of several large blocks of the margin in the next two years. Sonar data from these expeditions, along with the information and samples provided by ROV dives, represent important new baseline data sets that can be used to investigate possible methane-related impacts associated with climate, marine chemistry, benthic and water column biology and habitat, and the current tectonic state of the Cascadia margin.

The Cascadia margin exploration incorporated collaborators ashore and at sea from the Ocean Exploration Trust; NOAA Office of Ocean Exploration and Research, Pacific Marine Environmental Laboratory, Olympic Coast National Marine Sanctuary, Northwest Fisheries Science Center, and Southwest Fisheries Science Center; the University of Washington; and Oregon State University.

# Exploration of S/S *Coast Trader*

By James P. Delgado, Frank Cantelas, Lisa J. Symons, Michael L. Brennan, Deanna Bergondo, Richard Sanders, Evan Reger, Donald L. Johnson, Jacques Marc, Robert V. Schwemmer, Lea Edgar, and Duncan MacLeod

The beginning of the Cascadia margin cruise brought E/V *Nautilus* within range of a sonar target thought to be one of a handful of World War II combat losses on the Pacific coast. The freighter *Coast Trader*, reportedly torpedoed by the Japanese submarine *I-26* some 30 miles (48 km) off Cape Flattery on June 7, 1942, had never been located since it exploded and sank on that early June wartime morning after departing the Straits of Juan de Fuca with a cargo of newsprint (Figure 1). The crew survived the sinking, although one man perished while awaiting rescue, which was slow in coming.

*Coast Trader* is one of 87 wrecks identified during a multi-year study by NOAA (Symons et al., 2013) as posing potential pollution threats "within American waters"; the vessel was sunk early in its voyage, with a presumed near-full capacity of heavy fuel oil, calculated at 8,088 barrels. NOAA's Office of National Marine Sanctuaries and Office of Response and Restoration, the US Coast Guard, and other partners have updated that report as opportunities have arisen to add to understanding of the wrecks.

A 2010 Canadian hydrographic survey located a sonar target likely to be *Coast Trader* off Cape Flattery in 164 m of water on Canada's continental shelf. Given the wreck's potential pollution hazard to the northwest coast, a dive on the presumed *Coast Trader* was added to the 2016 *Nautilus* cruise to the Cascadia Margin (pages 28–29). A team of archaeologists and historians participated in the dive from the Inner Space Center and other locations on shore.

Nearly 74 years to the day that *Coast Trader* was sunk, the ROV dive quickly established that the wreck was *Coast Trader*, and that a single torpedo hit the starboard side at the number three hold, opening a substantial hole that quickly flooded the ship, causing it to sink by the stern (Figure 2). The stern struck bottom with considerable force, twisted, and collapsed. As the wreck hit the seabed, it appears to have catastrophically released as much as half of the oil in its fuel tanks. The forward section of the wreck, however, is substantially intact.

ROV dives documented artifacts such as a 37 mm deck gun, steam winches, anchors, and the ship's bell (Figure 3). A team from the US Coast Guard assessed the structural integrity of the hull, closely examining its plating seams, rivets, and corrosion. While the wreck's lighter steel superstructure and decks are corroded and have failed, the hull appears intact and without active corrosion. The key question is whether *Coast Trader* will soon collapse and catastrophically release the remaining oil. Based on this visual, in situ inspection, the team does not believe this will happen in the foreseeable future.

The dive on *Coast Trader* added to our understanding of this otherwise forgotten but important event in the history of World War II and provided the means by which a more detailed assessment of the wreck as both a historic site and a potential pollution hazard could be completed. This demonstrated that while wrecks with fuel left inside are a concern, some, like *Coast Trader*, do not need expensive mitigation at this time.

Figure 3 (right). Forecastle deck of *Coast Trader*, showing the anchor windlass and the ship's bell.

Figure 2 (left). The torpedo impact area is located on *Coast Trader*'s starboard side, in the area between cargo holds numbers three and four.


Figure 1. S/S *Coast Trader* at a dock in San Francisco, May 11, 1937. *Courtesy of San Francisco Maritime National Historical Park, Procter Collection, A01.37,080ps (SAFR 21374)*

# Mapping and Exploration of Deep-Sea Corals and Shipwrecks in the Greater Farallones National Marine Sanctuary

By Jan Roletto, Michael L. Brennan, Gary Williams, Christina Piotrowski, Guy Cochrane, James P. Delgado, Jamie Wagner, Ashley Marranzino, and Robert V. Schwemmer

In 2015, the Greater Farallones National Marine Sanctuary (GFNMS) was expanded, nearly doubling the area of protection. The Greater Farallones office also administers the northern portion of the Monterey Bay National Marine Sanctuary (MBNMS). Combined, this region encompasses one of the world's four major upwelling centers, areas where cold, nutrient-rich seawater rises from the deep to the surface, creating a globally significant marine ecosystem that supports abundant wildlife and valuable fisheries. The primary goals of cruise NA077 on E/V *Nautilus* were to explore three of the 400 shipwrecks within the extensive maritime cultural landscape of the GFNMS, characterize the deeper regions of the sanctuary through mapping and documentation of deep-sea corals and sponges, and share with the world a virtual excursion to illuminate the sanctuary's rich cultural heritage and its wildlife.

In particular, we explored the wrecks of USS *Independence* (pages 34–35), the freighter S/S *Dorothy Wintermote*, and the historic steam yacht S/S *Ituna* during this cruise (ONMS, 2014). We also investigated the roles these wrecks play as marine habitat for fish and invertebrates and explored some of the deepest portions of the sanctuaries at Arena Canyon, Farallon Escarpment, and Pioneer Canyon (within the MBNMS). We also took environmental DNA samples as part of a season-wide effort (see page 15).

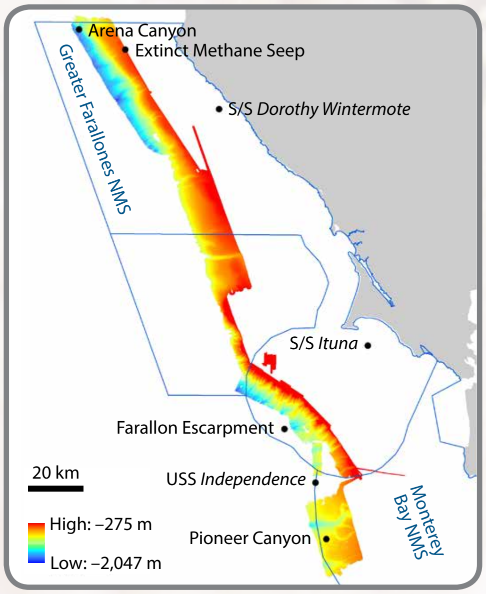



Figure 1. Approximate location of ROV dives (black dots) and areas of multibeam and backscatter data (colors) collected throughout the sanctuaries. The August cruise more than doubled the amount of seafloor mapped in the GFNMS.

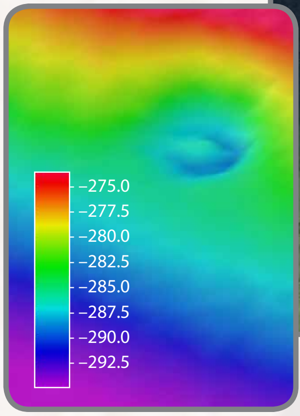



Figure 2. Multibeam map indicating the depression and mound of an extinct methane seep located west of Point Arena.

## Mapping

As an initial step in exploring the GFNMS, we collected multibeam data. Previous mapping efforts were completed by NOAA Ship *Okeanos Explorer* in 2009 and by the USGS using R/Vs *Snavely* and *Fulmar* in 2011, covering 1,029 km$^2$ (Dartnell et al., 2014; Figure 1). *Nautilus* mapped 1,600 km$^2$ in the deeper portions of Arena Canyon, Farallon Escarpment, and Pioneer Canyon, more than doubling the amount of GFNMS seafloor mapped with a modern multibeam echosounder.

## Extinct Methane Seep

During the mapping surveys, working west of Mendocino County, we discovered an unusual seafloor feature whose crest was approximately 60 m × 15 m at ~290 m water depth (Figure 2). An ROV dive revealed this feature to be an extinct methane seep that had built up a mound consisting of carbonate crust mixed with shell hash from the clams that once thrived on it. Now, the biology at this feature is typical of rocky outcrops and includes rockfish, sponges, and corals. Methane seeps have never before been identified within the Farallones region, making this feature unique and warranting further exploration.

## Arena Canyon

The northern wall of Arena Canyon displayed extensive deepwater coral reefs that featured a variety of species, including bamboo, bubblegum, black, and mushroom corals; primnoids (*Callogorgia* sp.); and Plexauridae (*Swiftia* sp.), many of which were sampled (Figure 3). ROV *Hercules* collected some of the first images of blob sculpins (*Psychrolutes phrictus*) guarding egg nests on top of rocks and near corals.

Figure 3. An abundance of bamboo and bubblegum corals on a rocky outcrop on the northern wall of Arena Canyon.

Figure 4. Close-up of a black coral (*Bathypathes* sp.) and a spot prawn (*Pandalus platyceros*) on a muddy outcrop along the Farallon Escarpment.

Figure 5. Close-up of the eight tentacles on each polyp of a bamboo coral (an octocoral) in Pioneer Canyon.

Figure 6. Looking aft on the starboard side of S/S *Ituna*, the galley area of the ship, with an overturned stove now serving as home to a wolf eel (*Anarrhichthys ocellatus*). The ship is also now habitat for many white plumose *Metridium* anemones and fish.

## Farallon Escarpment

The Farallon Escarpment is the portion of the continental slope just west of the Farallon Islands and the site where we specifically targeted black and bamboo corals for sampling. This area has many sedimentary rock outcrops. Taxonomic studies of the corals collected during this dive, including *Acanthogorgia* sp., *Parastenella ramosa*, *Bathypathes* sp. (Figure 4), and other black corals, are still underway.

## Pioneer Canyon

Bamboo and black corals have long been thought to occur in Pioneer Canyon, having been described in dive records from the submersible *Sea Cliff* in the late 1980s and early 1990s and also listed as bycatch in fishing trawl records. The high-definition camera on *Hercules* revealed many bamboo coral forests and rocky features with complex and diverse corals, sponges, other invertebrates, and associated fish (Figure 5). Taxonomists from the California Academy of Sciences, the Harvard Museum of Comparative Zoology, and the Royal British Columbia Museum are working to identify the specimens. Toward the end of the dive, we found a series of small munitions dumps, including disarticulated piles of bullets and ammunition boxes. We suspect that ships heading toward the ammunition dump far west of the canyon prematurely dumped their ammunition along this portion of the canyon.

## S/S *Dorothy Wintermote*

In 1938, the freighter S/S *Dorothy Wintermote* ran aground at Fish Rocks in Mendocino County just south of Haven's Neck. All lifeboats were launched, and the Coast Guard rescued everyone, including the ship's mascot, a tabby cat. The Coast Guard attempted to salvage the ship, but it was so badly damaged that it sank quickly. *Hercules* revealed that the hull from midships to the stern was intact, and many features, such as the engine room skylight, masts, winches, and steering gear, were still visible. Numerous anemones are growing on the wreck, and many fish were seen swimming around it. The wreck was examined for impacts from fishing gear and for signs that oil might potentially be released. Fortunately, the shipwreck looked sound.

## S/S *Ituna*

S/S *Ituna*, originally built in 1886 as a yacht and later converted to a fishing trawler, sank in a storm in 1920. Two of the crew were lost with the ship. *Hercules* was able to provide very good imagery, despite the high amount of zooplankton in the water column. The ship is completely encrusted with invertebrates and is corroding badly. This wreck acts as rocky habitat for white plumose anemones, at least 10 different species of rockfish, and at least one wolf eel whose territory includes an overturned stove in the ship's galley (Figure 6).

## Exploration Reveals Secrets of the Sanctuary

Although the E/V *Nautilus* cruise greatly expanded our understanding of the diversity and richness of the deep-sea communities of the Greater Farallones National Marine Sanctuary, we merely scratched the surface. The discoveries of the extremely high diversity of invertebrates and fish on and around the shipwrecks demonstrate the need for further investigation to quantify densities and gain a better understanding of the associations between our cultural and natural resources. It is important to determine whether nets snagged on these cultural resources have further damaged them, or whether corrosion is increasing, possibly leading to release of oil. The deep waters of the Greater Farallones National Marine Sanctuary are rarely explored, but ROV *Hercules* dives revealed many secrets of North America's most ecologically rich underwater treasures in San Francisco Bay's backyard.

# Exploration and Mapping of USS *Independence*

By James P. Delgado, Michael L. Brennan, Jan Roletto, Frank Cantelas, Russell Matthews, Kelley Elliott, Kai Vetter, Christopher Figueroa, Megan Lickliter-Mundon, and Robert V. Schwemmer

During World War II, the aircraft carrier USS *Independence* (CVL22) was “the lead ship of its class of light aircraft carriers that were critical during the American naval offensive in the Pacific” (ONMS, 2016). After the war, in early 1946, *Independence* was assigned to the target fleet for Operation Crossroads, the United States’ postwar naval tests of the atomic bomb at Bikini Atoll. After sustaining two atomic blasts, it remained afloat. The Navy then towed *Independence* to San Francisco, where it served as a platform for testing decontamination methods. Prepared for scuttling and storage of what was described at the time as “low level” nuclear waste, in January 1951, *Independence* was towed 48 km (30 miles) out to sea from the Golden Gate and sunk following detonation of two experimental torpedo warheads placed inside, below its waterline.

The ship next received attention in 1990, when USGS side-scan sonar images revealed its probable location. In 2009, NOAA’s Office of Ocean Exploration and Research confirmed the location using multibeam data. In 2015, OER, the NOAA Office of National Marine Sanctuaries, and The Boeing Company, utilizing a Coda Octopus® sonar system (Delgado et al., 2016) verified that *Independence* was upright on the seafloor in 900 m of water (Figure 1). The ship, lying within the Monterey Bay National Marine Sanctuary, was designated a priority for telepresence-enabled exploration during E/V *Nautilus* cruise NA077 (pages 32–33).

The 2016 ROV dives revealed that the carrier is embedded in the seafloor above the original waterline. Although historic accounts and photographs show *Independence* capsizing, the carrier righted while sinking, and the bow impacted the seabed first at an angle, digging into the sediment. The hull is distorted and broken just aft of the hawsepipes, demonstrating that the angle of impact was perhaps as much as 20%.

During our noninvasive survey, we completed photographic mapping and 40 hours of detailed video surveys of the hull, flight deck, sponson decks with their associated armament and other equipment, and island superstructure. ROV *Hercules* was also used for limited penetration of the hangar deck through the two open elevator shafts and access holes cut by the Navy before sinking the carrier. The wreck is covered in part with marine growth and displays some corrosion, though metal degradation due to microbial processes was noticeable but limited. The raised steel letters at the stern spelling “INDEPENDENCE” still retained paint (Figure 2). Frame numbers painted on the hull to simplify surveys of atomic bomb damage at Bikini were noted, and the faint remnant of what was likely the carrier’s battle record on the island superstructure was also observed.

The sponson decks retain all armament left on board for the atomic tests, including dual 40 mm antiaircraft guns, gunfire control directors, and single 20 mm antiaircraft guns (Figure 3). The two 20 mm weapons separated from the deck and lie on the seabed by the bow. Interior compartments could be

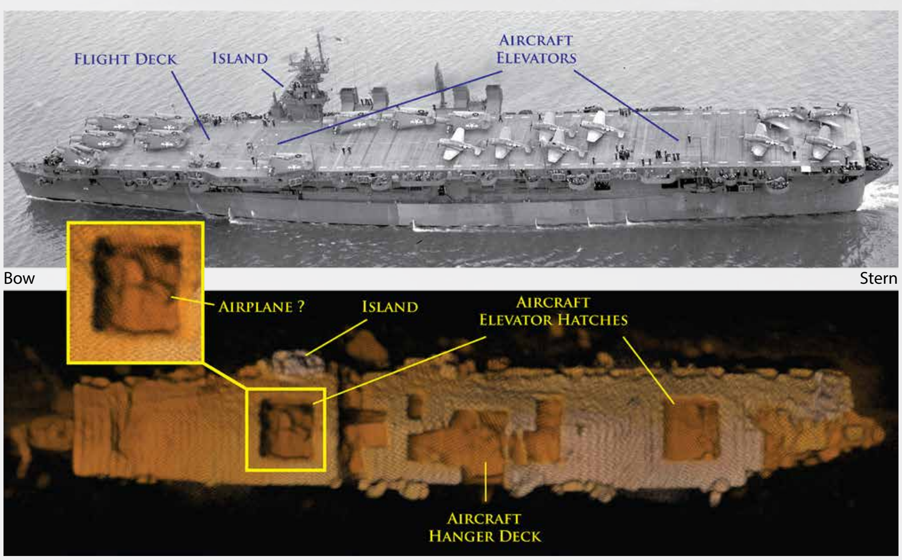



Figure 1. (top) USS *Independence. Photo credit: National Archives* (bottom) Dives during 2016 on USS *Independence* were aided by this Coda Octopus®-generated sonar image from the 2015 NOAA Office of Ocean Exploration and Research and Office of National Marine Sanctuaries/Boeing survey.

Figure 2. The raised steel letters spelling the carrier’s name retain some of their paint.

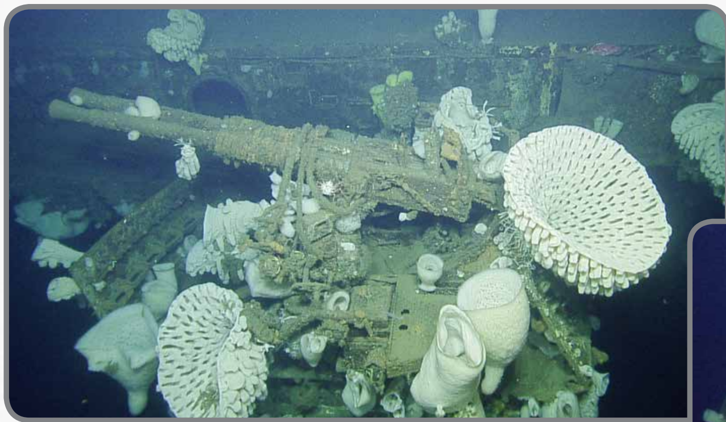


Figure 3. The sponson decks retain all of the armament and equipment left on board for Operation Crossroads.

Figure 4. A peak overpressure gauge tower used to mount test instruments at Bikini remains in place at the bow of *Independence*.

seen through open and missing hatch doorways. The overall impression was that *Independence* strongly resembles post-Crossroads photographs documenting its atomic damage.

The survey closely examined two prominent Crossroads artifacts. One was the tubular steel "peak overpressure gauge" towers used to mount test instruments at Bikini, which remains in place at the bow (Figure 4). The other was an aircraft indicated on 2015 sonar imagery and confirmed by the 2016 ROV dive to be an F6F-5N Hellcat. The aircraft was mostly intact inside the forward elevator well and partially filled with silt. It is missing the tail section, and one wing is broken near the fuselage, but it is in overall good metallurgical condition and has some paint remaining (Figure 5). The aircraft lies next to 50-gallon concrete-capped steel barrels, one of which was corroded, revealing that it was filled with rubber gloves.

Records indicate the placement of numerous aircraft as test instruments, the "destruction" of some, and the removal of one aircraft after testing in San Francisco. The aircraft discovered on *Independence*, however, proved to be one reported as destroyed by the first of the two atomic bomb tests, and afterward jettisoned. The Hellcat fighter was most likely blown by the blast into the elevator and left in place. No other aircraft are recorded to have been on board at the time of sinking, but the survey also discovered the broken wing of another aircraft, an SBF-4E Helldiver, lying on the hangar deck near an open side hangar door. This wing retains paint markings, interestingly the white base coat of the US Naval insignia roundel but not the upper paint layer of the insignia.

Another key aspect of the survey was determining if, after 70 years since its exposure to two atomic blasts, *Independence* remained radioactive. Under the guidance of Professor Kai Vetter, students of the University of California, Berkeley, RadWatch team collected eight sponge samples from the hull of *Independence* and two from Pioneer Canyon as controls for radiation measurements. The sponges were dried and examined with a high purity germanium detector for 24 hours. The measurements did not show any $^{137}$Cs or $^{60}$Co that could be attributed to Operation Crossroads or nuclear waste. They indicated only trace amounts of naturally occurring radioisotopes in concentrations comparable to samples from the California mainland.

Figure 5. The forward elevator contains a damaged F6F-5N Hellcat fighter placed aboard the ship for Operation Crossroads testing.

After mapping of the wreck was completed, we collected several sponge specimens for taxonomy. Vase, boot, and goiter sponges prevailed throughout much of the side and upper reaches of the ships. Several different small red and bronze fan corals were observed; most were 10 cm wide or less. The videos collected will be analyzed for ecological characterization of the invertebrates and fish on the wreck. Taxonomists have already identified a range extension of one species of sponge and one, possibly two, new species of sponges. On first assessment, it appears that *Independence* has one of the highest densities of sponges encountered in the sanctuary (Etnoyer et al., 2014).

The surveys of *Independence* were widely viewed, including during a 90-minute live broadcast of the start of the dive on The Weather Channel. There was also extensive participation from Scientists Ashore, as well as the public, who helped answer questions about the wreck, underscoring the benefits of telepresence-driven exploration. *Independence* evokes the dawn of the nuclear age and the Cold War, with substantial evidence of its 1946 role as a target ship as well as its subsequent use as laboratory. No longer radioactive from its use as an atomic target, it is both a museum piece and a habitat for marine life in Monterey Bay National Marine Sanctuary.

# Exploration of Central California Basins, Cold Seeps, and San Juan Seamount

By Nicole Raineault, Peter Girguis, Steve Auscavitch, Chris Castillo, Megan Lubetkin, Jeffrey Marlow, Dorothy Pak, Sarah E. Myhre, James Kennett, Amanda Netburn, and Renato Kane

The original plan for *Nautilus* cruise NA073 was to explore the Bodega, Arguello, and Partington central California canyon systems and the remote regions of Davidson Seamount. However, due to persistent strong winds and heavy seas, the cruise was relocated to more protected waters south of Point Conception. There, participating scientists investigated new areas of the water column and seafloor from the Santa Barbara Basin to San Juan Seamount. The explored habitats included pronounced oxygen minimum zones, diffuse hydrocarbon vents, and a deepwater seamount (the deepest dive of the season; Figure 1).

## Exploration of Santa Barbara Basin

As the ocean warms, oxygen minimum zones are expected to shoal, leading to expansion of low-oxygen conditions and a resultant shift in the distribution and assemblages of organisms. To better understand the extent to which natural gradients in dissolved oxygen might influence marine communities, we completed two ROV dives across the steep oxygen gradients on the southern and northern slopes of Santa Barbara Basin. Sediment cores collected from this basin have led to an important paleoenvironmental reconstruction of the last 150,000 years; accordingly, investigations into modern faunal zonations here inform interpretations of past climate warming and oxygen loss (Behl and Kennett, 1996; Cannariato et al., 1999; Moffitt et al., 2015).

Sediment samples, environmental measurements, and video transects were collected to examine the effect of changing oxygen levels, which ranged from ~6.6 µM at 540 m water depth to ~13 µM at 380 m, on the benthic ecosystem. Extensive microbial mats were noted in the deeper regions, and successional zonations of benthic fauna were obvious. Some microbial mats had dense epifaunal populations of the bacterivore gastropod *Alia permodesta*. Microfaunal assemblages in the sediment from 500 m to 480 m water depth were dominated by the benthic foraminiferal species *Bolivina argentea*. By 460 m, brittle stars and sea stars were evident, and the sediment samples showed abundant spatangoid (urchin) spines and a greater diversity of benthic foraminifera. From 440 m to 380 m, numerous invertebrates were observed (Figure 2). These records provide an opportunity to catalog the relationships between distributions of benthic communities and naturally occurring changes in dissolved oxygen concentrations, as well as interpret ancient sediment deposits to shed light on paleoclimatic conditions.

Another priority on this cruise was exploration of the water column in order to characterize the understudied midwater fauna of Santa Barbara Basin. At both the Goleta landslide complex and central Santa Barbara Basin sites, several 30-minute ROV transects were conducted at different depths

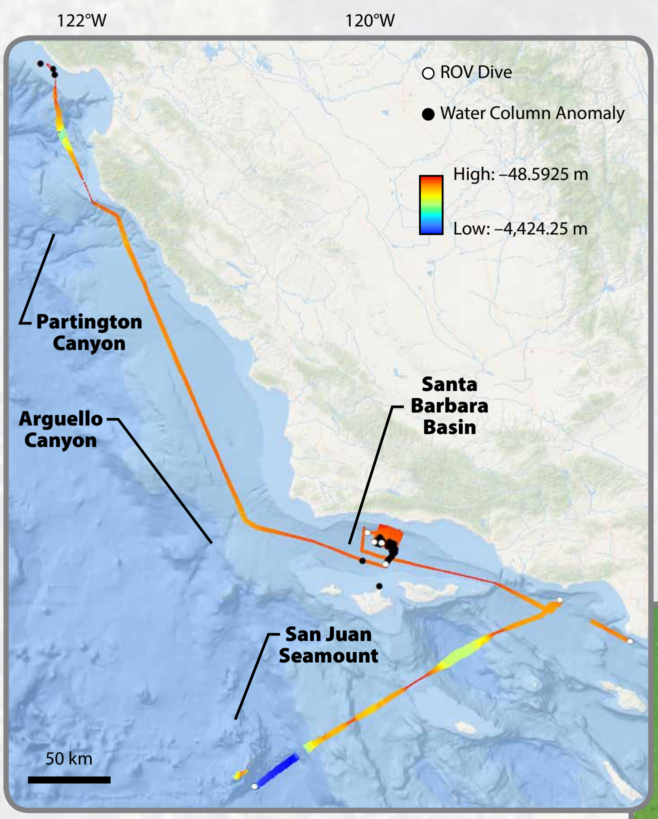



Figure 1. Figure depicting E/V *Nautilus* multibeam mapping coverage, water column anomalies, and ROV dive sites. *Service layer credits: Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors*

Figure 2. Numerous urchins, sea stars, brittle stars, and bivalve molluscs were observed on the shallower parts of one of the transects in Santa Barbara Basin (440–380 m depth).

across the oxygen minimum zone. We saw a variety of animals throughout the water column, including jellyfish, fish, siphonophores, ctenophores, shrimps, and copepods, and collected several jellyfish and fish for further study. A species of Bathylagidae (deep-sea smelt) was abundant throughout the water column and also frequently observed near the seafloor. There was preliminary evidence of faunal zonation, possibly related to declining oxygen concentrations with depth.

Figure 3. A novel instrument measures eH over one of the chimney-like constructions observed at the Point Dume site.

Figure 4. Coral, benthic fauna, and fish were observed at San Juan Seamount.

## Geochemical Exploration at Point Dume

To test a novel in situ Eh sensor, which measures electron activity, we visited a vast chemosynthetic habitat that was discovered during the 2015 *Nautilus* season. This extensive field of white, yellow, and orange microbial mats extends for ~1.3 km in a shallow sublinear north-south trending depression at Point Dume. This is likely a hydrocarbon-rich seep site supporting anaerobic methanotrophic, sulfate-reducing, and sulfide-oxidizing microbial communities. Despite the abundant microbial mats, no fluid flow or bubble ebullition was observed. Interspersed among the microbial mats, we observed abundant submeter vertical, chimney-like constructions (Figure 3). Such carbonate "reefs" have not previously been reported at marine methane seeps, although similar structures occur in the anoxic, methane-rich Black Sea. When sampled, a thin outer crust of rock fell away from the chimney to reveal an internal structure of black, likely sulfidic, sediment. Samples were collected for analysis, and initial experiments suggest the structures contain communities with elevated rates of methane oxidation.

## Exploration of San Juan Seamount

On the eastern margin of the Pacific Plate, west of the southern California continental shelf break, is a 30 km × 70 km northeast-southwest trending feature composed of eight volcanic pinnacles (Paduan et al., 2009). San Juan Seamount, which extends from a water depth of 560 m to 3,600 m, formed about 20 million years ago and then subsided below sea level as the oceanic lithosphere cooled and aged. The seamount's biological communities had not been thoroughly surveyed previously.

The southeast face of San Juan was explored starting at a depth of 3,350 m. The heavily sedimented rise of the seamount was dominated by soft-bottom taxa, including xenophyophores and echinoderms, while hard substrate was colonized by bamboo corals and sponges. Demersal fishes at bathyal depths consisted primarily of grenadiers, Pacific flatnose antimora, and halosaurs. Continuing upslope, the seafloor transitioned to muddy sediments with occasional gouges, similar to those ascribed to beaked whale marks (Auster and Watling, 2010). The sediment thinned at ~2,960 m, revealing basaltic cobbles and pillow lava. Elongate basaltic pillows were observed along the steeper ridge faces starting at 2,840 m. Exploded boulders and blowouts were observed among the pillow basalt fields. Multibeam and backscatter data revealed a distinct crater about halfway up the seamount and possible flat terraces just below. Varying slopes point to a dynamic geologic past as the seamount was constructed and subsided.

Along the seamount flanks (>1,600 m water depth), cold-water corals were sparse. However, between 900 m and 750 m, dense stands of gorgonian fans were observed, generally increasing in abundance and overall size toward the shallower end of the range. ʻAʻa lava flows and terrace-like features observed at ~700 m depth on the northwest face of the seamount indicate historical subaerial exposure. The final ascent of San Juan Seamount revealed many steep ridges with intermittent pillow lava regions and sediment patches. The summit was relatively flat, with basalt cobbles (<1 m) along the southwest ridgeline. Toward the seamount summit, soft coral gardens were prominent, at times in dense patchwork assemblages consisting of primnoid, isidid, and acanthogorgiid octocorals. Interspersed in these summit assemblages were mushroom corals and zoanthid species, often encrusting octocoral skeletons. Sponges and other suspension feeders were present throughout these assemblages (Figure 4). Stony, reef-building scleractinian coral colonies were notably absent, though solitary cup corals were occasionally observed.

This investigation of San Juan Seamount revealed patterns of deepwater benthic communities similar to those observed on other California margin seamounts (McClain et al., 2009). Additional surveys and analysis of biodiversity metrics are necessary to better establish ecological and biogeographic relationships between San Juan Seamount and regional deepwater communities.

# Mapping and Exploration Within and Surrounding the Channel Islands National Marine Sanctuary

By Dwight Coleman, Peter Etnoyer, Chris Caldow, Julie Bursek, Leigh Marsh, Will Sautter, Ryan Freedman, and Renato Kane

During July 2016, E/V *Nautilus* and the Corps of Exploration conducted a major research and exploration program within and surrounding the Channel Islands National Marine Sanctuary (CINMS) offshore southern California. The sanctuary was designated in 1980 to protect the natural and cultural resources around the five northern Channel Islands: Anacapa, Santa Cruz, Santa Rosa, San Miguel, and Santa Barbara. To carry out its mandate to manage these nationally significant regions, NOAA collects new data to help inform decision-making. This cruise included a large-scale multibeam sonar mapping effort to collect detailed bathymetric, acoustic backscatter, and video data, as well as samples both within CINMS and in regions outside of the sanctuary boundaries that are being considered by the public for designation as a new sanctuary and/or are of particular oceanographic interest.

While seafloor maps are a critical component of decisions ranging from navigational safety and disaster response to resource management and conservation, nearly 90% of the seafloor off southern California remains largely unmapped. Within the sanctuary, this number is nearly 50%. During cruise NA074, approximately 286 nm$^2$ (981 km$^2$) was mapped within CINMS, providing bathymetric data covering over one-third of the remaining gap within the sanctuary; an additional 420 nm$^2$ (1,441 km$^2$) was mapped outside the sanctuary (Figure 1). These data will provide an understanding of the geological structures and biological habitats associated with the local living marine resources, as well as aid in planning future oceanographic studies and informing management.

The team also completed 10 ROV dives to ground truth newly mapped terrain, revisit key locations where cold-water coral ecosystems thrive, and collect geological and biological samples, as well as high-definition underwater video and still imagery (Figure 1). The dives were planned in collaboration with many Scientists Ashore who helped identify locations of specific scientific interest and who participated virtually through telepresence during the dives to help collect more than 100 samples. Many samples were distributed to our shore-based partners for detailed analyses.

The first ROV dive was on a knoll west of Santa Barbara Island—the first ever ROV investigation within this unexplored part of the sanctuary. During the dive, we came across a region loaded with interesting and perplexing geological formations and a rich and diverse benthic ecosystem. At ~150 m depth near the top of the knoll, we saw large mudstone boulders, some of which were nearly perfectly spherical, or large, smooth, and oblate; some had the shape of saucers, others the shape of cupcakes (Figure 2). This type of rock formation commonly forms along high-energy coastal environments such as rocky headlands adjacent to beaches. When seafloor at this depth was exposed during lower sea level stands, the sediment that makes up the mudstone remineralized to form a hard core that is more resistant to weathering than the

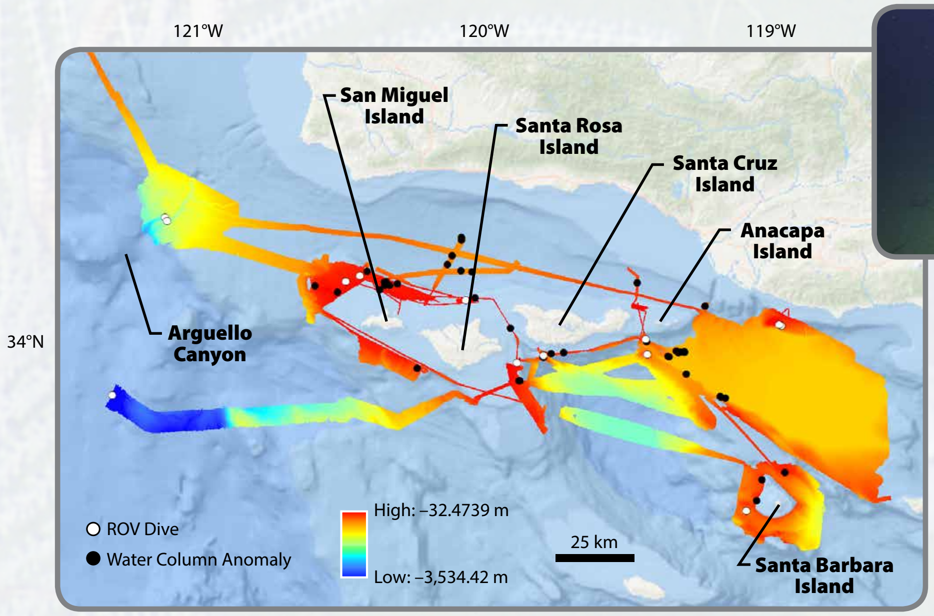



Figure 1. Figure depicting E/V *Nautilus* multibeam mapping coverage and depth, water column anomalies, and ROV dive sites. *Service layer credits: Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors*

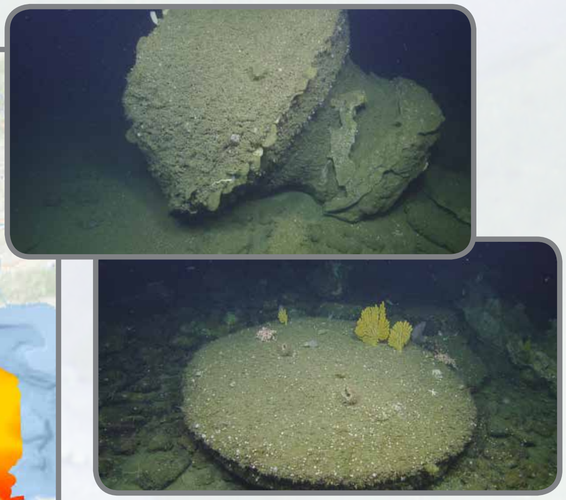
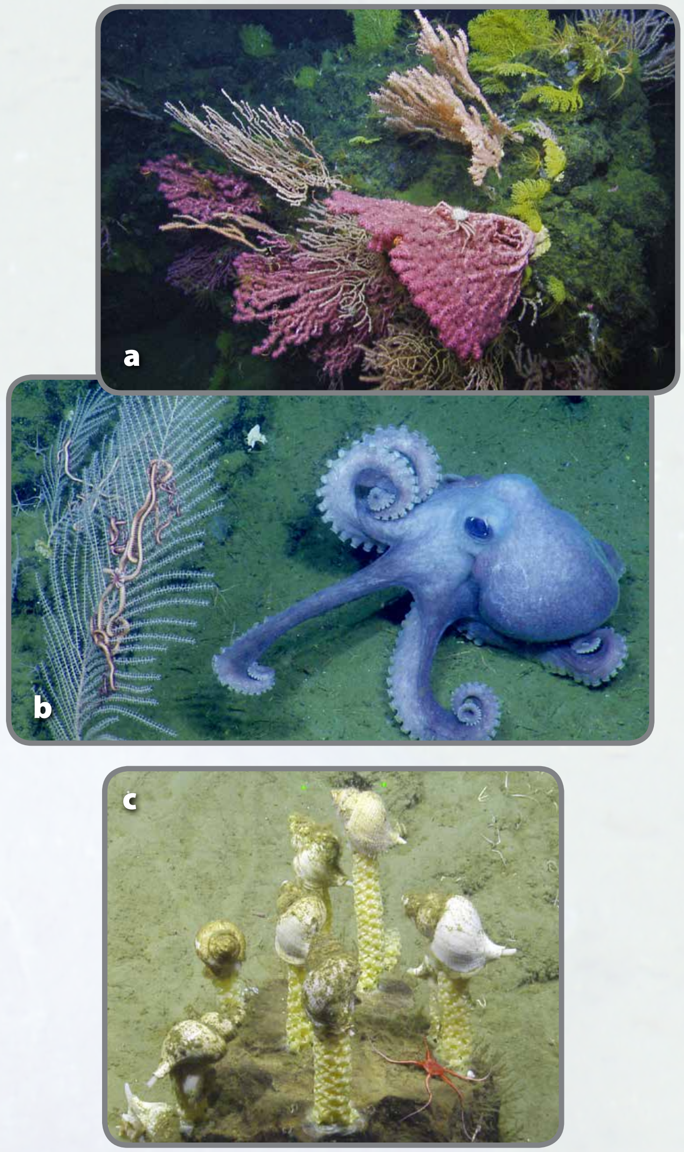


Figure 2. Mudstone concretions were discovered off Santa Barbara Island at depths ranging from ~150 m to 275 m. They were likely formed by ancient coastal sedimentary depositional processes associated with paleoshorelines.

Figure 3. The community around cold-water corals on Footprint Reef includes rockfish and purple sea fans.

Figure 4. (a) The top of the south wall in Arguello Canyon was composed of a deep-sea "coral garden" with many large bubblegum corals (bright red), bamboo corals (orange and white), and Plexauridae sea fans (yellow). (b) A Graneledone octopus approaches a pair of tall Primnoidae sea fan corals with ophiuroid brittlestars attached at 1,650 m depth. (c) A whelk nursery was observed along the west levee.




substrate in which it sits. The rock formations were exposed at an ancient shoreline for long periods of time, leaving the mudstone boulders behind as the sediment substrate eroded away. The boulders became submerged due to rising sea level and tectonic subsidence, depositing them in their current location and configuration.

Two dives surveyed low relief, rocky ridge features north of Santa Rosa Island and west of San Miguel Island, contributing to an ongoing characterization of the Channel Islands shelf habitat. The dives encountered hundreds of orange and purple sea fan corals (*Adelogorgia* and *Eugorgia*), with attendant schools of colorful rockfish (Figure 3). Many live samples were collected and shipped to cold-water aquaria for further study. The surveys will support conservation and management of these sanctuary areas, which lie outside of adjacent marine protected areas.

We conducted two dives in and around a selected deep-water portion of Arguello Canyon. Shore-based scientists suggested conducting an ROV dive where the axis of the submarine canyon is offset by active fault splays associated with the San Andreas Fault system. Sonar mapping of the region revealed canyon walls with formations that were likely exposed by faulting and scoured by turbidity currents, exposing bedrock and creating habitat for benthic fauna. These dives were the first look at this dramatic undersea feature, which has been proposed to NOAA as a new national marine sanctuary.

The two dives in Arguello Canyon made a series of five wall climbs from 1,800 m to 1,500 m depth, three on the steep southern wall and two on the gentle northern slope. There were many deep-sea corals on the steep southern wall, but they were sparse until the top of the wall, where thousands of red, yellow, and white sea fan corals were observed. Many of the colonies were 1–2 m across and included bubblegum and bamboo corals (Figure 4a). More than a dozen Grenelodone octopuses were seen (Figure 4b). On the gentle northern slope of Arguello Canyon, the ROV encountered a very different but equally diverse assemblage, including large crabs, corallimorph anemones, *Acesta* clams, a whelk nursery (Figure 4c), and a mysterious "purple orb" (see page 16).

During this cruise, we experimented with innovative sampling techniques and technologies. Working with a team from Harvard University, the ROV *Hercules* manipulator was equipped with a new set of "squishy fingers," soft robotic grippers for collecting delicate benthic animal samples (see page 12). The bulk of the preserved samples were deep-sea corals, which are common at these depths and important to research. We collected live specimens of coral that were immediately delivered ashore and kept alive in the laboratory (see page 17); they continue to grow and are monitored and studied at the NOAA Center for Coastal Environmental Health and Biomolecular Research. While all samples collected are of scientific interest, the mysterious purple orb was an international phenomenon (see page 16).

# Exploration of the Southern California Borderland

By Marie-Helene Cormier, Katherine L.C. Bell, Stephanie M. Sharuga, Chris Castillo, James Conrad, Diva Amon, Mark Legg, Michael L. Brennan, Kelsey Barnhill, Lawrence L. Lovell, Ashley Marranzino, Simon L. Klemperer, and Renato Kane

E/V *Nautilus* cruise NA075 returned to the Southern California Continental Borderland, an area that remains largely unexplored. Part of the broader North America-Pacific plate boundary, this region extends ~300 km west of the San Andreas Fault and displays an unusually rugged physiography. During the cruise, the multibeam sonar mapped ~5,200 km$^2$ of seafloor, and ROVs *Hercules* and *Argus* were deployed for 16 dives to explore geological and biological targets (Figure 1) and collect samples.

## Submerged Marine Terraces

Submerged marine terraces provide information about ancient sea levels, vertical tectonic motion, plate boundary evolution, and seismic hazards. In 2015, *Nautilus* explored submerged marine terraces exposed in a submarine canyon near Santa Catalina Island. Fossils recovered from rock samples provide age constraints for the deepest submerged terraces surrounding the island (Castillo et al., 2015). We continued the transect in 2016 to determine the ages of Santa Catalina's uppermost terraces. We targeted seismic horizons that corresponded to a time when the terraces were exposed on land during the Wisconsinan (~20,000 years ago) and Illinoian (~145,000 years ago) glaciations when sea levels were ~100 m lower. Radiometric dating of these samples will constrain the position of Santa Catalina's shoreline during the first human occupation of North America. Similar dives were conducted on several shallow submerged banks to investigate vertical tectonic motion and to establish activity on numerous offshore faults in the California Continental Borderland.

## Fault Zones

The Santa Cruz-Catalina Ridge and Ferrelo active fault zones were explored on several dives. Dive tracks targeted fault zones exposed in canyon walls, and ROV observations revealed some characteristic expressions of active faults. Pressure ridges—elongate ridges with relief of up to a few hundred meters that mark convergence along a strike-slip fault—were identified from our new multibeam bathymetry and then investigated with *Hercules*. We mapped a pressure ridge within a narrow "hillside valley" on the flank of Santa Cruz-Catalina Ridge and another at the base of Southwest Bank and found both consistent with large-scale transpressional structures. The large extent of these features suggests infrequent large earthquakes ($M_w$7) and potential for local tsunami generation.

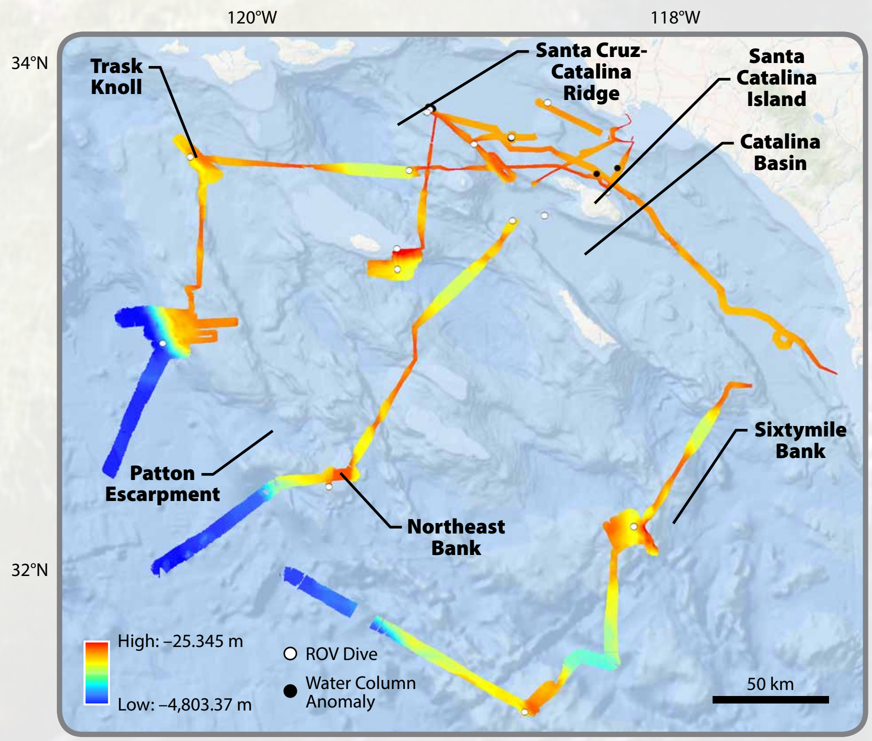



Figure 1. E/V *Nautilus* multibeam mapping coverage, water column anomalies, and ROV dive sites. *Service layer credits: Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors*

## Cold Seeps

We visited three seep areas associated with known faults or folds and explored a water column anomaly in Santa Monica Basin that turned out to be a large seep site with two distinct provinces—flat in the north and hummocky in the south. White, gray, orange, and yellow bacterial mats were present as well as one bubble plume (0.35°C) and a low abundance of megafauna, likely due to low oxygen concentrations (~1.8 µM). Seismic data collected by the USGS in 2014 suggested the possibility of cold seeps on Kimki Ridge in Catalina Basin, and we explored two of the three potential sites. The first was covered by a widespread layer of authigenic carbonate and patches of whitish microbial mats, and was littered with dead clams. The second showed substantially more evidence of seepage, including a greater abundance of live clams, microbial mats, and authigenic carbonate.

## Seamounts and Guyots

Shallow banks occur throughout the offshore California Continental Borderland. We mapped four of them and then visited them with *Hercules*. Their flat summits, now lying in 120 m to 550 m of water, are interpreted to have been subaerial in the geological past and are now subsiding. Trask Knoll, Southwest Bank, and Sixtymile Bank were uplifted as a result of tectonic activity on a set of northwest-oriented faults, as evident from the bathymetric data, and as interpreted from existing seismic reflection profiles. Northeast Bank, on the other hand, is a volcanic guyot (Paduan et al., 2009). Rock samples collected from presumed ancient shorelines on all four banks are awaiting analysis to constrain their rates of subsidence.

## Deep-Sea Biogeography

Megafaunal communities in this region varied greatly by location, depth, and benthic habitat characteristics. Exposed rocks and outcrops served as diversity hotspots, hosting a variety of sponges, tunicates, brittle stars, crinoids, and anemones (Figure 2). Squat lobsters, hermit crabs, serpulid calcareous tubeworms, bryozoans, and nudibranchs were also present in smaller numbers. Asteroids, holothurians, ophiuroids, echinoids, shrimps, hexactinellid sponges, and several species of crabs were associated with both soft and hard seafloor. Multiple kinds of deep-sea octocorals were observed along with some hard coral species, particularly at seamounts and in heavily rocky areas, but were overall not abundant. Other notable fauna include sea pigs, jellyfish, sea pens, acorn worms, scallops, and seep-related benthic communities.

Benthic-dwelling rockfish from the family Sebastidae, common to the Pacific coast, were frequently observed during dives. These fishes—notable for their venomous spines, long lifespans, and fisheries importance—were observed over a wide depth range (100 m to ~1,400 m) and were often found in rocky seafloor areas. The most common species was *Sebastolobus alascanus* (shortspine thornyhead), along with other *Sebastes* spp. rockfish. Other common fishes encountered included grenadiers, soles, morid cods, eelpouts, sablefishes, hagfishes, snailfishes, occasional *Bathysaurus* sp., snipe eels, skates, catsharks, and chimaeras (*Hydrolagus* spp.).

Several species of cephalopods were observed in this region. The giant Pacific octopus (*Enteroctopus dofleini*) was found at almost every dive site (Figure 3), and there were multiple sightings of *Graneledone boreopacfica* and *Grimpoteuthis* sp. (i.e., dumbo) octopods. The googly eyed stubby squid (*Rossia pacifica*) as well as other squid species were encountered.

## Whale Falls

During *Nautilus* cruises NA074 (see pages 38–39) and NA075, four previously undiscovered whale falls were found southeast of Santa Rosa Island (90 m depth), on Sixtymile Bank (370 m depth), on Northeast Bank (437 m depth), and on Patton Escarpment (1,094 m depth), all at late stages of decomposition. These are among the shallowest natural whale falls discovered worldwide thus far. The Santa Rosa skeleton is small compared to the other falls and lies in well-oxygenated water, while the others are located within oxygen minimum zones (10–25 µM). The Sixtymile Bank skeleton is that of a mysticete, but its species cannot be determined without a DNA sample from one of the bones. This skeleton was mostly intact, unsedimented, and undegraded, with many bones still in place (Figure 4). The carcass on Northeast Bank was highly degraded and covered with a lot of sediment, and thus may have been on the seafloor for years to decades. Furthermore, several animals were using the bones as hard substrate and for shelter. On the Patton Escarpment whale fall, urchins were grazing on the bones that also showed evidence of microbial mats, suggesting there was still energy in the bones despite their degraded state. There was no visible evidence of *Osedax* or other whale-fall-endemic fauna on any of the carcasses.

Figure 2. Vibrant pom-pom anemones, *Liponema brevicornis*, and a large boot glass sponge occupied by shrimps made up this rocky undersea garden.

Figure 3. A giant Pacific octopus, *Enteroctopus dofleini*, camouflages itself among brittle stars, anemones, serpulid tubeworms, and other encrusting species on a rocky outcrop.

Figure 4. The whale skeleton located among large rocks on Sixtymile Bank was host to several animals, including a coral, a sponge, and sea stars.

# Exploration and Information to Meet National Needs with NOAA Ship *Okeanos Explorer*

By Craig Russell and David McKinnie

NOAA's Office of Ocean Exploration and Research (OER) is the only federal agency dedicated to exploring the global ocean. OER works with partners to identify priority areas for exploration, support innovation in exploration tools and capabilities, and encourage the next generation to pursue careers in ocean exploration and related fields. The data collected during our expeditions and the research we fund gives resource managers, the academic community, and the private sector the information they need to identify, understand, and manage ocean resources for this and future generations.

The ocean is largely unexplored, unknown, and unseen by human eyes. Using NOAA ship *Okeanos Explorer*'s deep submergence and telepresence technologies, OER collects data that enables characterization of the deep ocean. New high-resolution maps of the seafloor, geological and biological samples and images, and data on ocean chemistry make the science community, decision makers, and the public aware of the significance of the deep ocean environments.

OER is responsible for coordinating the national ocean exploration program, a framework that encourages federal agencies, academia, the private sector, and foundations to collaborate to address national ocean exploration priorities. *Okeanos Explorer* and ROVs *Seirios* and *Deep Discoverer* are important contributions to the national ocean exploration infrastructure.

*Okeanos Explorer* crew deploys NOAA's remotely operated vehicle *Deep Discoverer.*


## NOAA Ship *Okeanos Explorer*

LENGTH | 68 meters (224 feet)

BEAM | 13 meters (43 feet)

DRAFT | 5.1 meters (16 feet, 10 inches)

DISPLACEMENT | 2,312 LT

MAIN PROPULSION | Diesel electric with twin inboard turning screws (1,600 Shaft HP)

SPEED | 10 knots

ENDURANCE | 40 days at sea

RANGE | 17,780 kilometers (9,600 nautical miles)

DYNAMIC POSITIONING (DP-1) | 500 HP retractable azimuth bow thruster and two 250 HP stern thrusters

BUILT | 1987, Halter Marine in Pascagoula, MS, USA

BERTHING | 49 persons (26 crew, 23 mission/science)

FLAG | United States of America

HOME PORT | North Kingstown, RI, USA

*Note: All images in the* Okeanos Explorer *section of this publication are credited to NOAA OER unless otherwise indicated.*

# New Technologies for Ocean Mapping

By Elizabeth Lobecker, Derek Sowers, and Mashkoor Malik

## 1.2 Million Square Kilometers of Deep Sea Mapped

With completion of the 2016 expeditions, the NOAA Office of Ocean Exploration and Research and NOAA Ship *Okeanos Explorer* have mapped over 1.2 million km$^2$ of seafloor around the world since the ship began its exploration mission in 2008 (Figure 1). This is equivalent to mapping the land area of California three times over. OER pursues every opportunity to collect and archive valuable acoustic data from unmapped areas of the seafloor using the ship's suite of modern sonars, including strategically planning oceanic transits to collect data over key unmapped areas. Examples include consultation with the US Navy to map seamounts important to submarine navigation and with NASA and the Woods Hole Oceanographic Institution to map along oceanic fracture zones (Figure 2). These data sets have contributed to global understanding of Earth's oceanic ecosystems, and have spurred new major discoveries such as the methane seep province of the US Atlantic seaboard (Brothers et al., 2013) and the identification of numerous high-density deepwater coral communities on seamounts and submarine canyons.

## Telepresence-Enabled Mapping

Through telepresence, OER utilizes a high-bandwidth satellite connection to enable remote users to participate virtually in ocean research and exploration cruises. OER has been leveraging telepresence capabilities since the early 2000s, enabling remote users to support operational planning and execution, troubleshoot hardware and software, and examine data acquired during exploratory ocean mapping and remotely operated vehicle missions.

Telepresence technology has been increasingly integrated into normal operations for 24-hour-per-day mapping cruises on *Okeanos Explorer* as a means to enable experienced expedition coordinators and mapping team leads to guide the expedition from shore. In previous years, straight-line transit cruises that did not require extensive coordination from onboard OER personnel were used as test beds for utilizing telepresence to expand the relatively small mapping team's ability to support offshore operations. Telepresence Seafloor Mapping in the Pacific Remote Islands Marine National Monument—Wake Island Unit, an 18-day expanded transit cruise focused on seamount mapping (Figure 3)—provided the opportunity to test the telepresence mapping model further. The mapping team was split between shore-based and shipboard mission members (Figures 4 and 5). An onboard team of mapping experts executed the mapping objectives as defined in advance by OER on behalf of the science and management community, including data acquisition and quality control over six seamounts and strategic transit lines. An onshore team based at the Exploration Command Center at the University of New Hampshire received and processed all raw data sets on a daily basis and provided overall direction and oversight to the mission team to ensure cruise objectives were successfully met.

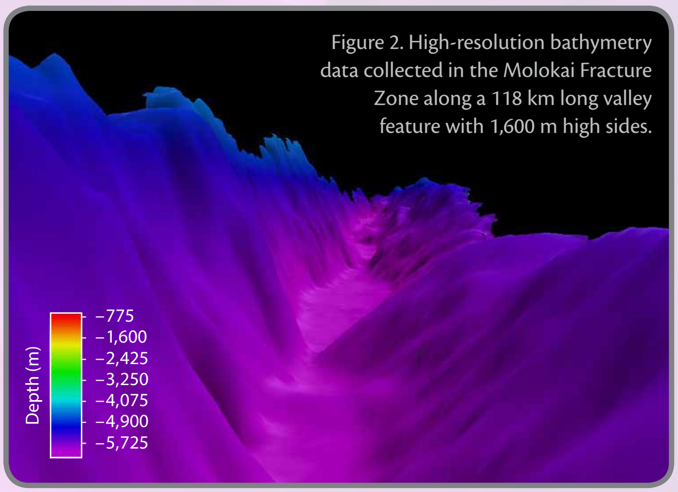



Figure 2. High-resolution bathymetry data collected in the Molokai Fracture Zone along a 118 km long valley feature with 1,600 m high sides.

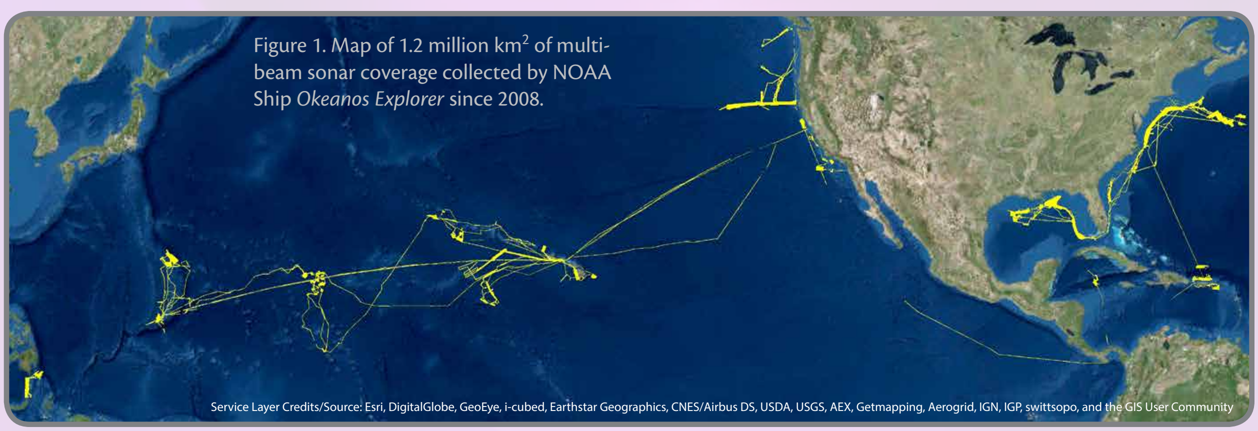



Figure 1. Map of 1.2 million km$^2$ of multibeam sonar coverage collected by NOAA Ship *Okeanos Explorer* since 2008.

## Remote Access

Remote access to the ship's network and sonar acquisition computers was enabled through the use of a virtual private network. Akin to ship's bridge training simulations, shoreside scientists and Explorers-in-Training took control of the ship's sonars, executing equipment settings changes and data management routines. A tolerable two- to four-second delay was experienced onshore while performing this work on the ship's equipment through remote desktop.

## Bandwidth and Data

Previously, typical *Okeanos Explorer* mapping cruises utilized a 5 Mbps satellite connection, which allowed a single live video feed, daily transfer to shore of summary bathymetry mapping grids, and normal Internet communications. Telepresence mapping was tested with 10 Mbps, which provided for two live video feeds to display sonar acquisition screens, hourly automated transfer to shore of all raw sonar data, and normal Internet communications.

Table 1. Bandwidth requirement for telepresence mapping cruise on NOAA Ship *Okeanos Explorer*. Bandwidth calculation does not account for signal loss or other usage such as Internet communication traffic or remote desktop access.

| DATA TRANSFER TYPE | DATA RATES PER 24 HR CYCLE |
|---:|---|
| Total Daily Raw Sonar Data Transfer (multibeam bathymetry, multibeam water-column, split beam water column, subbottom profiler, ancillary support files) | ~12,300 MB (~12.3 GB) |
| Two Live Video Feeds (2 × 3 Mbps × 86,400 seconds/day) | 518,400 MB (~518.4 GB) |
| Total Daily Bandwidth Required | 530,700 MB (530.7 GB) |
| DAILY REQUIRED BANDWIDTH (total of above/seconds in a day) | 6.14 Mbps connection |
| **TOTAL PLANNED BANDWIDTH** | **10 Mbps** |

## Benefits of Telepresence Mapping

1. Faster data processing, quality control, production of value-added products, and public archiving. The hourly delivery of raw sonar data to shore allows for more rapid quality control and analysis. Larger and more diverse types of data sets can be utilized by a larger group of experts than typically can sail on a ship. This will lead to more rapid dissemination of new discoveries through faster data analysis, production of value-added data products, and swift data archiving following initial data acquisition.

2. Rapid and secure backup of mapping data during the cruise. Typically, mapping data are not available on shore until hand carried or mailed once the ship makes port. However, telepresence-enabled mapping operations provide near-real-time data backup up at a second secure site independent of the ship's network storage.

3. More efficient management of experienced personnel's time and expertise. Telepresence technology has allowed more experienced scientists to continue their productive work onshore while providing input and expertise to newer team members on the ship. As NOAA OER builds partnerships within the ocean science and management communities, field seasons lengthen, and mapping platforms of opportunity become more available, the demand for seasoned mapping experts' time increases. Telepresence enables senior hydrography leads to collaborate more effectively with the broader marine science and management community on the delivery of value-added products, more effectively plan future cruises, and integrate new technology into *Okeanos Explorer* operations.

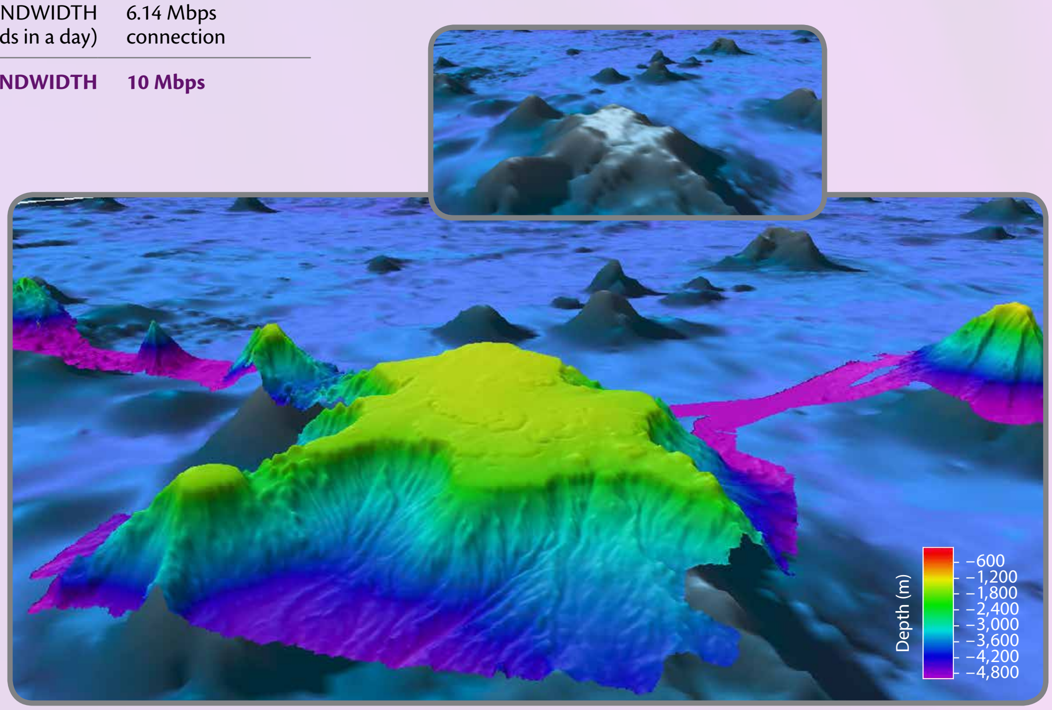



Figure 3. McDonnell Seamount, the largest of 29 seamounts mapped within the Wake Island Unit of the Pacific Remote Islands Marine National Monument as part of CAPSTONE. The inset shows publicly available satellite data (Sandwell et al., 2014) prior to CAPSTONE mapping.

Additional benefits are anticipated for future telepresence mapping cruises. Having a nimble team on board to collect and transmit high-quality data to geographically dispersed teams on shore allows for the incorporation of additional cruise objectives. These can include training of increased numbers of next-generation explorers, pre-training of scientists slated to sail in the future, and active cruise participation by individuals who cannot sail due to a variety of physical, personal, or professional reasons. Finally, telepresence mapping can potentially broaden multidisciplinary applications of ocean mapping cruises, including outreach, education, and communications efforts focused on expanding public understanding and benefits of ocean exploration.

As new technology for increased data compression becomes available and satellite bandwidth costs decrease, it is reasonable to expect to see this method of cruise execution become more common. The mapping team is currently planning for three telepresence mapping cruises during the 2017 expeditions.

## New Approaches to Existing Technology

The *Okeanos Explorer* mapping team has streamlined its mapping and data archiving methods, and opportunities to incorporate additional technology have been created. Five new sonars were made operationalized for the 2016 expeditions: three EK60 split-beam sonars with frequencies 70, 120, and 200 kHz, and two acoustic Doppler current profilers (ADCPs) with frequencies 38 and 300 kHz. All were methodically incorporated into standard data collection and archiving procedures and are now part of mapping and/or ROV dive routines. The additional EK60s demonstrated the potential to enhance OER's ability to detect hydrothermal activity in the water column (see pages 60–65) and to identify regions of the water column with dense aggregations of biological scatterers to be explored with ROVs. ADCP data estimating the velocity and direction of currents as deep as 1,000 m beneath the ship provide valuable situational awareness to ROV pilots prior to launch and throughout dives. As the team's understanding of the applicability for these data sets in ocean exploration develops and their potential is communicated to the science and management community, they will be further incorporated into the exploration cruise planning and execution process.

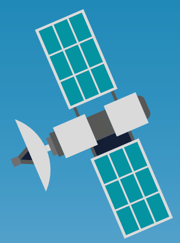
Figure 4. Explorers-in-Training Chloe Baskin and Caroline Cooper use telepresence technology at the University of New Hampshire Exploration Command Center to analyze data during Telepresence Seafloor Mapping in the Pacific Remote Islands Marine National Monument – Wake Island Unit.

Figure 5. Physical Scientist Lindsay McKenna and Survey Technician Charlie Wilkins conduct deepwater mapping in the Marianas Trench Marine National Monument.

# Telepresence: Sending Imagery from the Seafloor to Your Screen

As you sit at home or in your office watching the live video from NOAA Ship *Okeanos Explorer*, you are seeing information between 2.5 and 30 seconds after it is captured by NOAA's remotely operated vehicle (ROV) *Deep Discoverer* (*D2*). There is no sunlight deep in the ocean, so *D2* illuminates the area around the ROV to enable cameras to capture imagery.

Before imagery recorded by *D2* on the seafloor arrives on your screen, the content has been encoded, transformed, re-encoded, retransmitted, and decoded numerous times during a more than 50,000-mile journey from the seafloor to your eyes. Let's follow, in simplified terms, the path of one photon of information produced by *D2*.




1

## 0 seconds

The camera on *D2* captures a photon, a particle of visible light, records its properties such as wavelength and intensity, and then encodes that information into an electrical current. That electrical current is turned into a digital signal, which is transferred to photons. Using a laser, the information travels up the eight-kilometer cable that connects *D2* to *Okeanos Explorer*.

2

## 0.00003 seconds

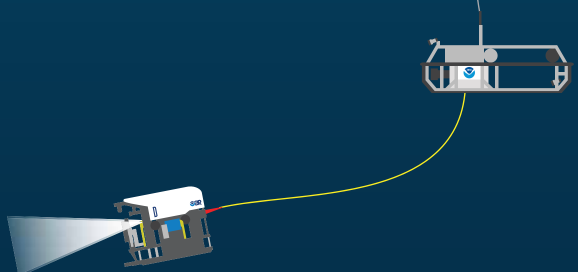
Once the photon is received on the ship, the information it carries is converted back into an electrical signal that flows over copper cables around the ship until it reaches the video encoders. The encoders take the digital video signal contained in the electrical signal and convert that information into a different type of digital information known as IP (Internet Protocol)-based video.

3

## 0.5 seconds

The encoder sends the new IP-based video out on Ethernet cables to the satellite modem where the digital signal is encoded on a radio wave. The radio wave is then amplified several times and transmitted to a geosynchronous satellite that is about 22,000 miles above Earth's surface.

The satellite receives the signal and then rebroadcasts it back to Earth. There is another modem in southern California that listens for the radio signals from the satellite. The receive modem takes the information contained in the radio waves and converts it back to an electrical signal.




## 2.5 seconds

After the electrical signal leaves the teleport, the information flows from southern California to Silver Spring, Maryland, on a dedicated connection. Once it reaches the NOAA network operation center, the traffic is handed off to Internet2, which is a special high-bandwidth Internet that is run and maintained by universities across the country.

## 20–30 seconds

For those without an Internet2 connection, there are a few more steps before you get to see the video. The Inner Space Center at the University of Rhode Island takes the video off Internet2 and transcodes it to a different type of IP-based video that will work on the standard Internet. This signal is then sent to YouTube.

When you open your web browser and hit play on the video window, your computer sends a request to YouTube for their servers to send a copy of the video to your computer. Once your machine receives the signal from YouTube, it converts the signal one last time from the electrical signal your computer received into photons that travel from your screen into your eye.

After more than 50,000 miles of travel in less than 30 seconds, the information from the bottom of the seafloor has been converted from photon to electron, back to photon, to an electron, then to a radio wave, then back to an electron when it reaches your computer. Finally, your computer uses the “information” that was encoded on all these different signals to create one last photon that represents one pixel of your screen that is transmitted to your eye. This photon is the same wavelength and a similar relative intensity as the original photon that was captured 30 seconds ago (2.5 seconds on Internet2) in the middle of nowhere on the bottom of the ocean.

# Exploring the Ocean Through Data

By Sharon Mesick, Susan Gottfried, Carrie Wall-Bell, and Jonathan Jackson

Data may not be the first thing people think of when imagining the exciting world of ocean exploration, but data are actually what exploring is all about. Every video, water column sample, and sonar scan is part of the picture of our ocean that NOAA Ship *Okeanos Explorer* is helping to develop. These data, when carefully stewarded, are also the tangible and enduring assets that illustrate the return on investment in ocean exploration.

The OER Data Management Team, led by NOAA's National Centers for Environmental Information (NCEI), implements and shares innovative tools and techniques developed to ensure multidisciplinary data collections are easily accessible, readily reusable, and available in perpetuity. *Okeanos Explorer* begins collecting data as soon as it leaves port. While the ship is at sea, the public can use the *Okeanos Explorer* Atlas (https://explore.noaa.gov/okeanosatlas) to follow its route and get a preview of information processed onboard ship daily. The companion web portal, the OER Digital Atlas (https://explore.noaa.gov/digitalatlas), provides simple access to the entire catalog of the OER data collection—covering more than 300 missions. The OER Digital Atlas contains links to a wealth of information, including post-cruise environmental data, dive summaries, and publications. The volume and variety of data collected during an expedition is extensive. The joint OER-NCEI Data Management Team ensures all data are quality assured, documented, and made available to the public as soon as possible.

## Innovation in Video Data Management

In the last seven years, *Okeanos Explorer* has collected almost 120 terabytes of underwater video data, encompassing over 70% of the information managed by the OER Data Management Team. The complexity and sheer volume of this collection represent unique challenges in enabling direct online access to these important environmental data. To meet these challenges, the Video Data Management Modernization Initiative aims to provide direct online access to the complete collection of digital video collected by deep submergence systems operated from *Okeanos Explorer* from 2010 to present. In addition to fulfilling its goal to meet OER's data needs, some components of this innovative video management system may be used to help other programs with the complex issue of video data management.

The OER Video Portal (Figure 1; https://www.nodc.noaa.gov/oer/video) provides access to thousands of hours of high-definition video and makes finding the desired video easy in a self-service model. It allows users to locate video segments based on specified search criteria, to stream and download selected video segments, and to place an order for online delivery of the same segments in full, broadcast-quality resolution.

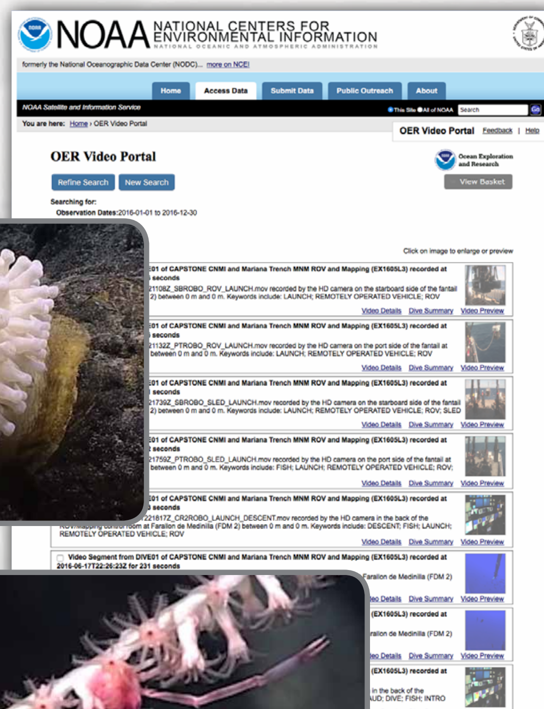



Figure 1. Users can search the OER Video Portal using geospatial, temporal, and environmental criteria, including descriptive keywords or phrases applied to time-stamped video segments by expedition scientists.

## Simplifying Access to Sampling Data

ROV sampling data have been newly integrated into online data access tools. A customized Sampling Operations Database Application records the location, depth, and environmental conditions at the time a specimen is collected. Scientists then add ancillary attributes and specimen images to this unique database once each specimen is processed in the onboard wet lab. The *Okeanos Explorer* Atlas (Figure 2) provides scientists with new insights into the biological and geological characteristics of the explored areas, including rare and newly discovered species.

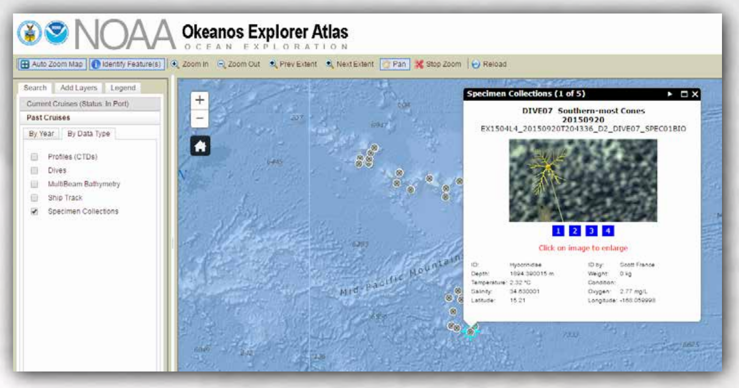



Figure 2. The *Okeanos Explorer* Atlas provides easy access to information about shipboard sampling operations. The atlas displays locations of all specimen collection sites on a map, and each location can be opened to view images and attributes of specimens collected there.

## Partnering for Shared Success

NCEI, in partnership with NOAA's National Marine Fisheries Service (NMFS) and the University of Colorado, is leading the management and reusability of water column sonar data collections (Figures 3 and 4). Data collected by shipboard echosounders are used to estimate biomass, measure fish school morphology, and characterize habitat. These instruments produce large volumes of data that are often stored locally and can prove difficult to access directly. For the stewardship and distribution of water column sonar data, the partners have created a national archive that contains over 32 terabytes of data accumulated since it was established in 2013. While NMFS is the largest source for this data collection, *Okeanos Explorer* is the second largest contributing vessel to the archive. User requests indicate a desire for OER data among the community, representing 53% of the 19.7 terabytes of data requested. The Water Column Sonar Data Map Viewer (https://www.ngdc.noaa.gov/maps/water_column_sonar) enables users to view trackline data where water column sonar data were collected, query, and request the raw data.

The benefits of a sustained OER-NCEI partnership include continued preservation of OER's valuable data, global access to an unprecedented data set, and the increased potential for researchers to explore OER data to address new questions and advance marine science. Data that are easily discoverable and accessible provide valuable information beyond their original collection purpose.

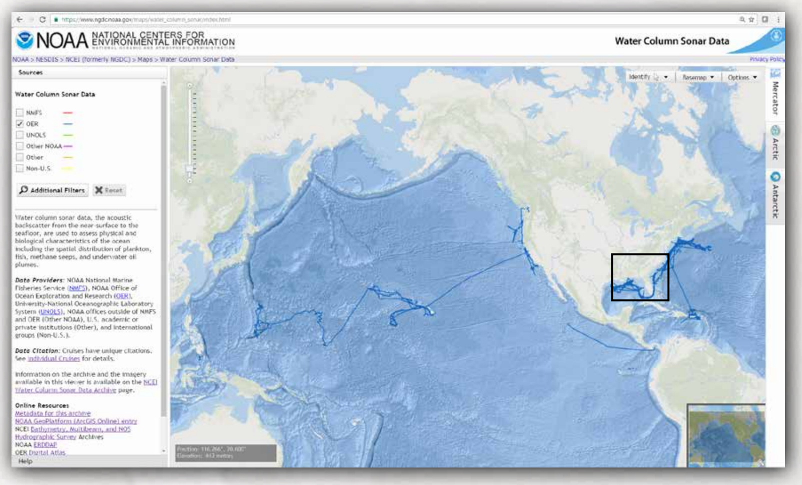
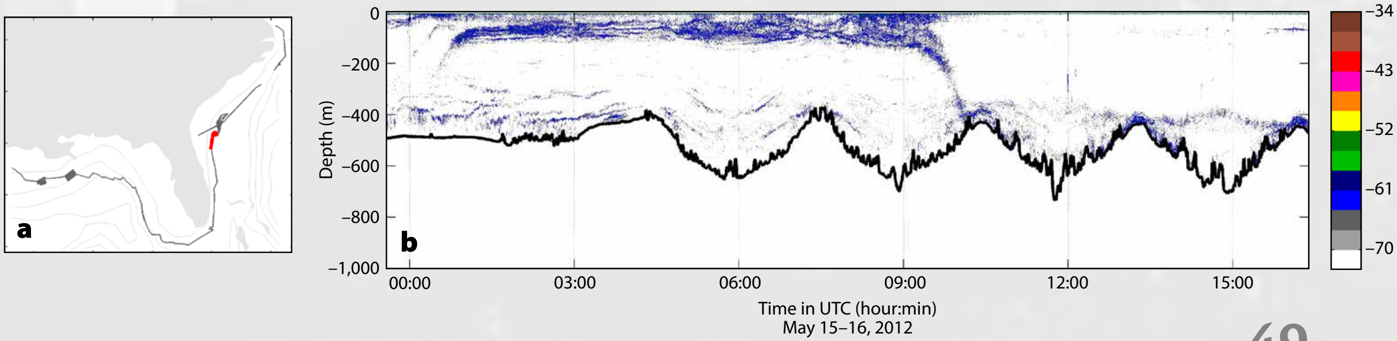



Figure 3. The NOAA National Centers for Environmental Information water column sonar data access page displays tracklines for all archived OER data in a separate layer. These cruises were conducted from 2009 to 2016.

Figure 4. Water column sonar data collected onboard *Okeanos Explorer* in 2012. The black box in Figure 3 shows the area where the cruise was conducted. (a) The red line shows where this file was recorded with respect to the entire cruise track (gray line). (b) Over this 15-hour period, diel vertical migration of the deep scattering layer was recorded. The black line shows the estimated seafloor.



# Value to the Nation

## Surveying and Data Management for the US Extended Continental Shelf Project

By Margot Bohan and Jennifer Jencks

The US Extended Continental Shelf (ECS) Project is a multi-agency partnership whose mission is to establish the full extent of the US continental shelf, consistent with international law (i.e., determining the outer limits of marine areas beyond 200 nautical miles where the United States can exercise sovereign rights over natural resources of the seabed and subsoil). It is also the largest and potentially most significant marine mapping initiative ever undertaken by the United States. To date, the project has yielded 17,000 linear kilometers of seismic data and more than 2.5 million km$^2$ of seabed mapped at high resolution. These areas encompass a multitude of seabed energy, mineral, and living marine resources potentially worth many billions of dollars.

The collection and analysis of data and samples that describe the depth, shape, and geophysical characteristics of the seabed and subseafloor are requisite for determining the outer limits of the continental shelf. NOAA leads the collection of bathymetric data for seabed mapping and characterization, and the US Geological Survey leads the collection of seismic data for subseafloor characterization.

NOAA's NCEI leads the data stewardship effort. The primary tasks are to gather, describe, and provide access to all ECS-related data and products, and to maintain the long-term ECS archive. This archive will eventually include the hundreds of data points that define the US ECS maritime limit.

In 2016, NOAA funded several cruises in areas ranging from the Pacific to the Arctic in order to meet US ECS Project objectives and ultimately to contribute to scientific baselines in often remote, poorly understood environments.

Scientists from the University of New Hampshire (UNH) led the first survey of the season aboard R/V *Kilo Moana* in the Kingman Reef-Palmyra Atoll area. A second NOAA and UNH sponsored Kingman-Palmyra ECS survey aboard NOAA Ship *Ronald H. Brown* completed reconnaissance of the regional platform from which the Line Islands seamounts and islands rise. The survey also collected data for the Republic of Kiribati, in support of that island nation's ECS efforts. Excluding transits, a combined total area of 313,675 km$^2$ (91,453 nm$^2$) was mapped (Figure 1).

In the western Pacific, a NOAA/UNH-led team aboard M/V *Fugro Supporter* surveyed along the Mariana Arc, the West Mariana Ridge, and an unsurveyed portion of the Mariana Trench (Figure 2). In addition to supporting the US ECS Project objectives, this effort is expected to clarify the process by which the breakup of the Mariana Arc

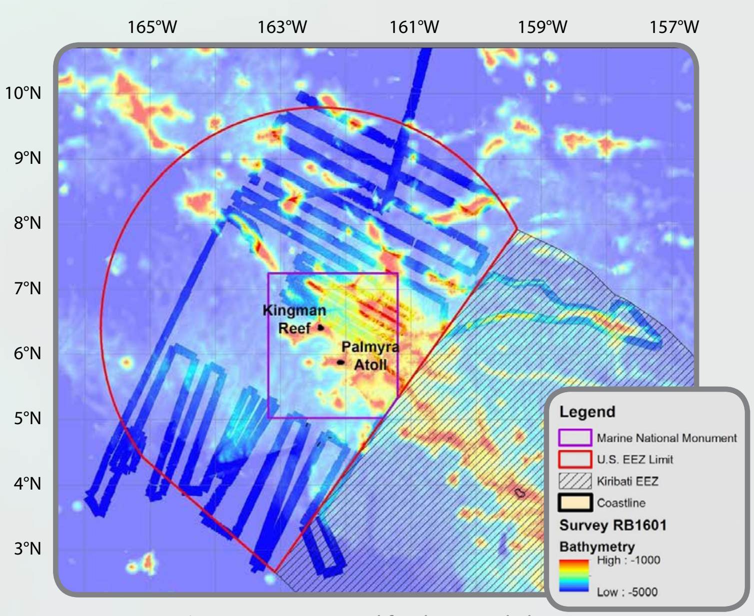



Figure 1. Areas mapped for the Extended Continental Shelf (ECS) Project during the 2016 field explorations by NOAA Ship *Ronald H. Brown*.

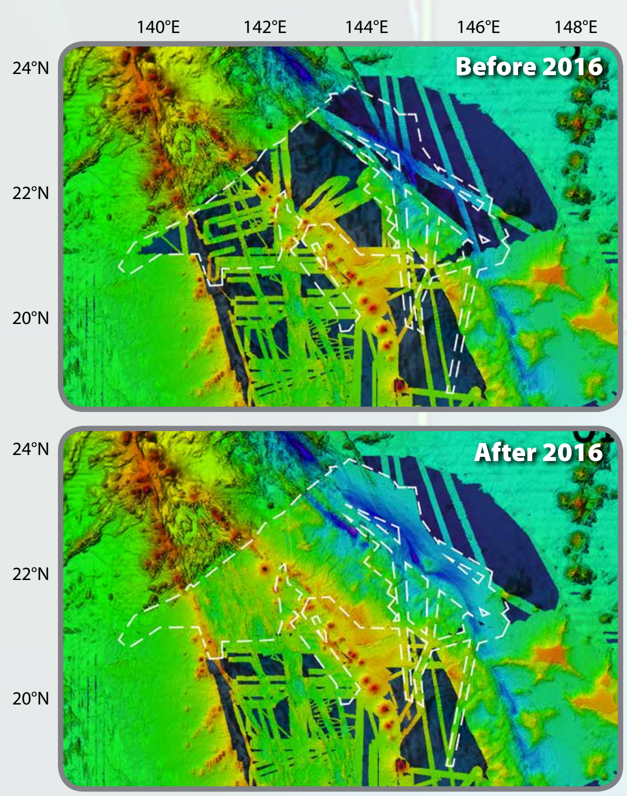



Figure 2. Before (top) and after (bottom) the 2016 ECS Mapping Survey of the Northern Marianas. The white dashes indicate the area mapped in 2016.

occurred—testing two competing hypotheses about the nature of the oceanic crust in the northern part of the wishbone-shaped area. Along the southern and central portions of the Mariana forearc, serpentinite mud volcanoes mark the locations of fluid escape above the subducting Pacific slab. Mapping between the arc and trench to the north, where subduction is highly oblique, will demonstrate whether these uncommon volcanic features are present everywhere in the Mariana system or whether they occur only where plate convergence is greatest. Altogether, 102,440 km$^2$ (29,867 nm$^2$) of seafloor were mapped during this 30-day survey (Figure 2).

In the Arctic, NOAA and UNH sponsored the tenth and final ECS field survey aboard US Coast Guard Cutter *Healy* (Figure 3). Priorities included collection of dredge samples on Alpha Ridge and bathymetric data in the Bering Sea and along the Beaufort margin. This information will help define the outer edge of the continent beneath the ocean along the US Arctic coastline. Approximately 14,000 km$^2$ of seafloor were mapped and 27 kg (60 lbs) of rock were collected and cataloged (Figure 4).

In addition to helping the United States determine its shelf outer limits, these data can be used to support research on climate and earthquake predictions, provide input for coastal zone management, and characterize seabed habitat. ECS data have also been useful in planning survey lines for *Okeanos Explorer* cruises and to conduct preliminary ROV dive planning in far offshore areas that cannot be mapped in advance. These data will continue to tell compelling stories and open up new scientific avenues that can be pursued for decades to come.

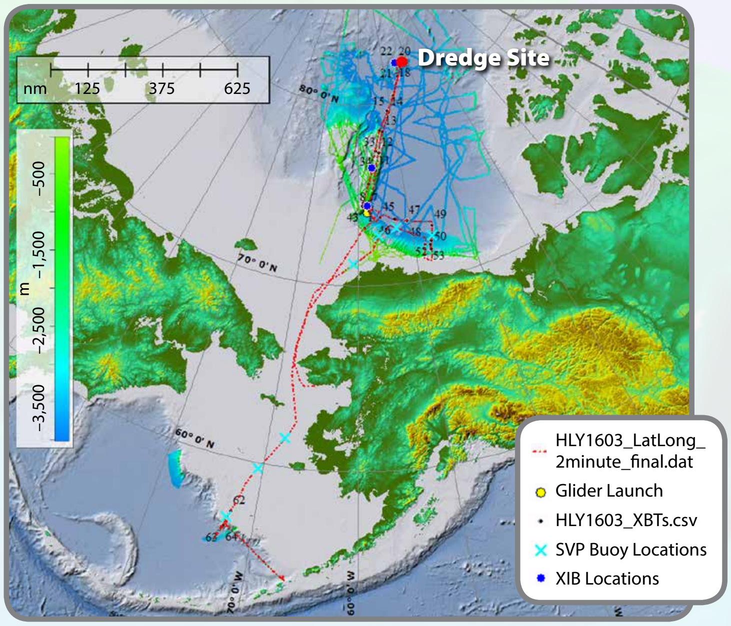



Figure 3. ECS surveys conducted in the Arctic. The red dash line indicates the 2016 survey area.

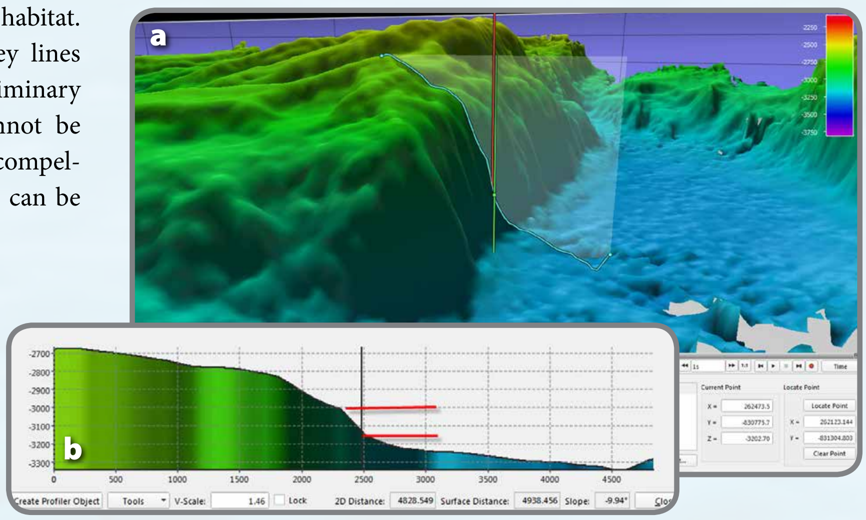


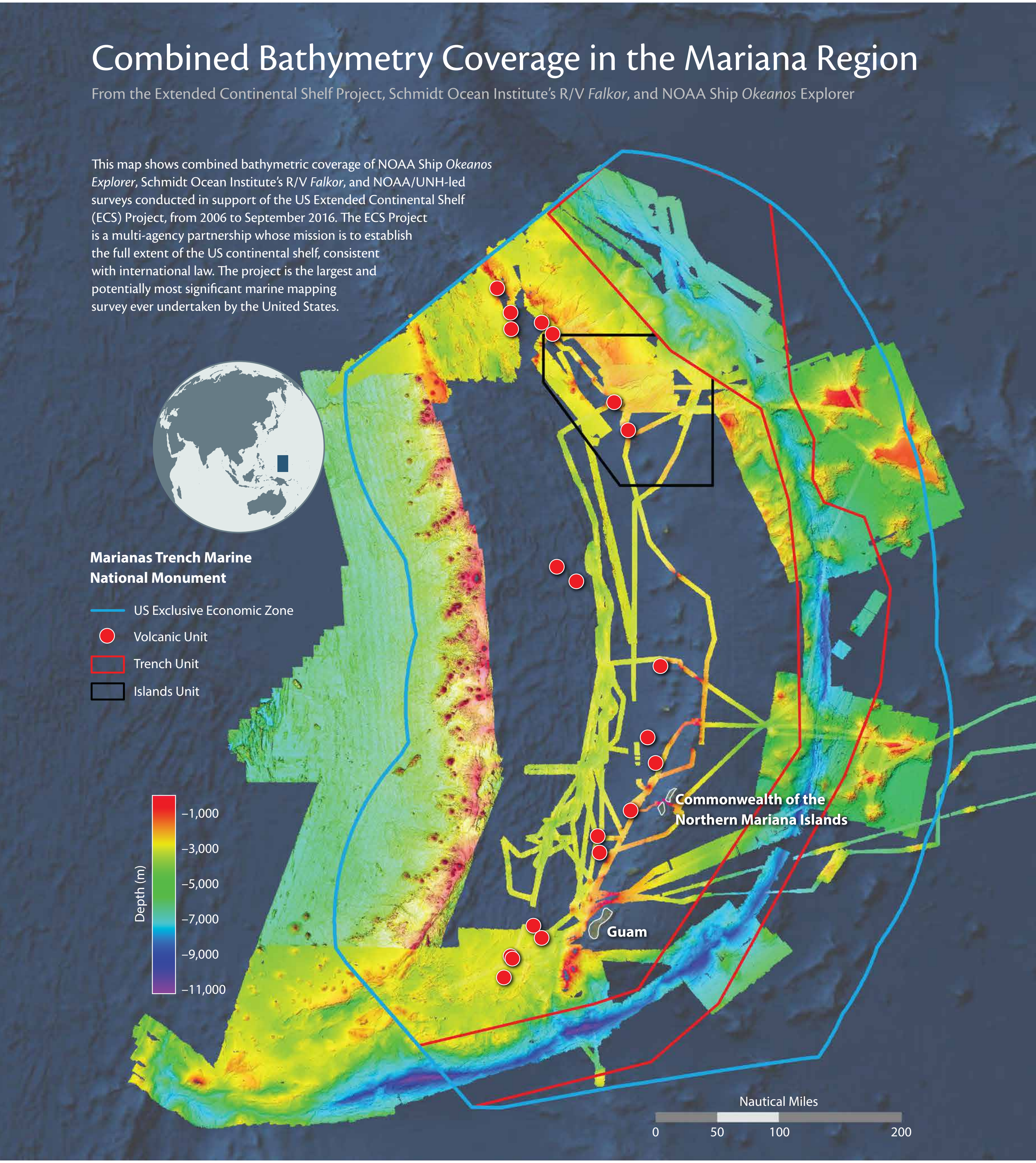


Figure 4. (a) Rock samples were collected within the watermarked area on Alpha Ridge, a major volcanic ridge in the Arctic Ocean. (b) The primary dredge site can be seen in this profile between the two red lines. (c) This photo shows a sample of what appears to be volcanic tuff retrieved from the first dredge deployment. Tuff is a type of rock made of volcanic ash ejected during a volcanic eruption. Following ejection and deposition, the ash is compacted into a solid rock in a process called consolidation.

# Combined Bathymetry Coverage in the Mariana Region

From the Extended Continental Shelf Project, Schmidt Ocean Institute's R/V *Falkor*, and NOAA Ship *Okeanos* Explorer

This map shows combined bathymetric coverage of NOAA Ship *Okeanos Explorer*, Schmidt Ocean Institute's R/V *Falkor*, and NOAA/UNH-led surveys conducted in support of the US Extended Continental Shelf (ECS) Project, from 2006 to September 2016. The ECS Project is a multi-agency partnership whose mission is to establish the full extent of the US continental shelf, consistent with international law. The project is the largest and potentially most significant marine mapping survey ever undertaken by the United States.



# CAPSTONE

## Exploring the US Marine Protected Areas in the Central and Western Pacific

By Samantha Brooke, Christopher Kelley, Randall K. Kosaki, Michael Parke, Frank Parrish, Amy Bowman, and Jeremy Potter

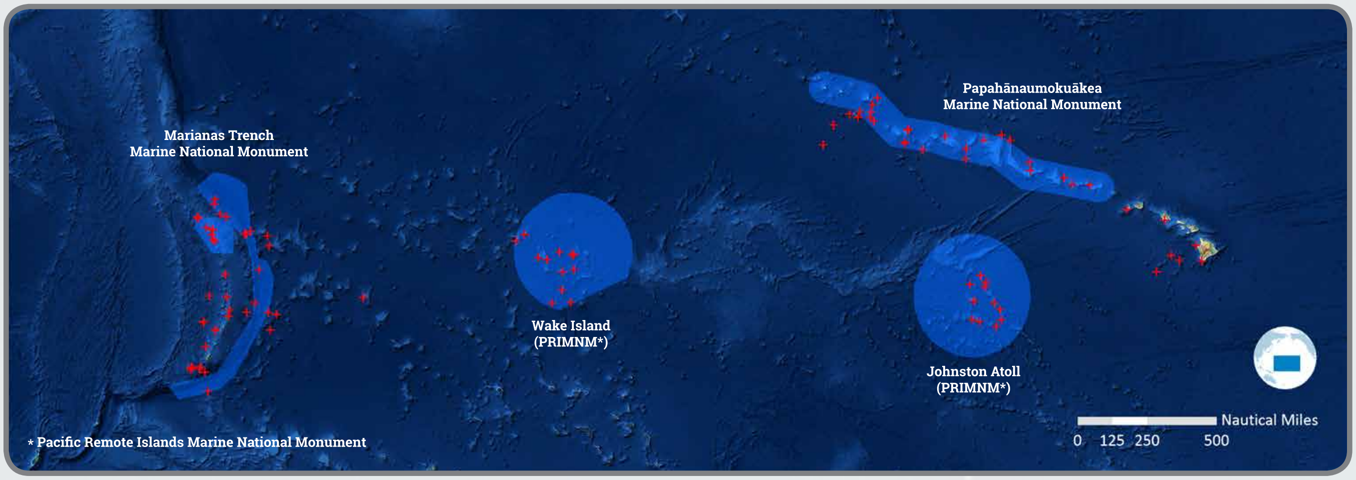
CAPSTONE is a multiyear foundational initiative to collect deepwater baseline information in and around US marine protected areas in the central and western Pacific. These areas contain some of the last near-pristine deepwater marine ecosystems on the planet and include numerous fish and invertebrate species, as well as a variety of geological formations, undiscovered shipwrecks, and other cultural heritage sites. Initial characterization of these Pacific MPAs advances scientific understanding, introduces the uniqueness of these areas to the nation, and helps explain why it is so important to protect them. Because these undersea regions are poorly known, the data and information collected by NOAA Ship *Okeanos Explorer* can inform the federal, state, and US insular agencies charged with MPA management responsibilities.

NOAA and its partners initiated CAPSTONE expeditions aboard *Okeanos Explorer* in July 2015. In addition to providing valuable information on the habitats and species in these MPAs, CAPSTONE also aims to contribute publicly accessible baseline data and critical information needed to respond to emerging regional issues such as deep-sea mining, sustainable deep-sea fisheries, and potential US ECS designation.

CAPSTONE relies on extensive cross-NOAA support and collaboration, as well as interagency and academic partnerships, to both set priorities and conduct exploration expeditions. CAPSTONE partnerships within NOAA include the National Environmental Satellite, Data, and Information Service; the National Marine Fisheries Service; the National Ocean Service; Oceanic and Atmospheric Research; and the Office of Marine and Aviation Operations. The US Geological Survey, the University of Hawai'i, Hawai'i state government agencies, and insular government agencies in Guam and the Commonwealth of the Northern Mariana Islands are key external partners. Other organizations, such as the Schmidt Ocean Institute, are also contributing critical baseline information about the deep ocean in CAPSTONE priority areas.

ROV *Deep Discoverer* is prepared for deployment on *Okeanos Explorer's* aft deck.

Map of the 2015–2016 CAPSTONE dives.



## 2015–2016 CAPSTONE Summary

NOAA's Office of Ocean Exploration and Research coordinates CAPSTONE activities on behalf of NOAA. These expeditions utilize telepresence technology, allowing teams of scientists to collaborate with and guide expeditions from shore-based Exploration Command Centers around the world or from homes and offices. To date, over 200 scientists, student researchers, and managers have participated in CAPSTONE expeditions, exploring unknown and little known deepwater areas.

CAPSTONE expeditions include 24-hour operations consisting of ROV dives, mapping, and limited biological and geological sample collection. In the first two years of CAPSTONE, NOAA conducted 14 cruises that included 102 ROV dives and mapped nearly 300,000 km$^2$ of seafloor in and around the poorly known deepwater areas of the Papahānaumokuākea Marine National Monument, the Johnston and Wake Atoll Units of the Pacific Remote Islands Marine National Monument, and the Marianas Trench Marine National Monument.

**Biology.** Nearly every ROV dive yielded biological discoveries. During the 2016 Deepwater Exploration of the Marianas expedition, surveys were conducted to gain knowledge about the largely unknown midwater biome as well as deepwater habitats. Since CAPSTONE's inception, hundreds of different types of animals have been identified from visual surveys of the seafloor and water column, including cnidarians, sponges, echinoderms, arthropods, molluscs, tunicates, bryozoans, ctenophores, siphonophores, fishes, and squid. Of these, 175 were identified as potentially undescribed species, and 182 were collected for further analysis and submission to repositories in the United States. These discoveries will increase understanding of biogeographic patterns across the central and western Pacific.

### CAPSTONE Science Themes

- Acquire data to support priority monument and sanctuary science and management needs
- Identify and map vulnerable marine habitats—particularly high-density deep-sea coral and sponge communities
- Characterize seamounts in and around the Prime Crust Zone—the area of the Pacific with the highest concentration of commercially valuable deep-sea minerals
- Investigate the geologic history of Pacific seamounts, including potential relevance to plate tectonics and subduction zone biology and geology
- Increase understanding of deep-sea biogeographic patterns across the central and western Pacific

**Geology.** Exploration of the Pacific's seafloor allowed scientists to examine extinct calderas, active volcanoes, mud volcanoes, fresh lava flows, rift zones, a variety of rock formations, seamounts, carbonate platforms, and other seafloor features. While exploring the largely unmapped Moloka'i Fracture Zone between California and Hawai'i, the Mission System Shakedown 2016 detected four previously unknown seamounts, some with interesting-looking crater features. In addition, mapping of the fracture zone also revealed an impressive 118 km long linear valley with 1,600 m tall steep-sided walls measuring 6 km from rim to rim. Scientists also documented the first-ever petit-spot volcano (young intraplate volcano) in US waters, as well as three new hydrothermal vent sites, while exploring in the Marianas. Rock samples collected during the Deepwater Wonders of Wake expedition could potentially change our understanding of the geologic history of the region as well as of Pacific Plate tectonics around 100 million years ago. In total, 178 geological samples were collected during this campaign and sent to the Oregon State University Marine Geology Repository for archiving.

This beautiful jellyfish from the genus *Crossota* was seen in the Marianas Trench Marine National Monument on April 24, 2016, during exploration of the informally named Enigma Seamount at a depth of ~3,700 m. Note the two sets of tentacles—short and long.

In the center of the photo, fluid emanating from a hydrothermal vent looks like dark smoke due to the high levels of minerals and sulfides in it. The chimney is crawling with *Chorocaris* shrimp and *Austinograea wiliamsi* crabs.

**Education and Outreach.** Providing information about the CAPSTONE region to the public is an important objective of the campaign. Online coverage of CAPSTONE expeditions, including live video feeds, were streamed to shore throughout, allowing thousands of members of the public to join ROV dives and explore the ocean virtually along with the scientists participating in expeditions. Live video from the expeditions received approximately 4.8 million views, and the expedition web pages received over 1.4 million views. Expedition information and observations were shared through social media venues including Facebook and Twitter. The OER Twitter account gained over 18,500 new followers, and tweets reached nearly 6,000,000 users. OER's Facebook account gained over 59,000 new likes, and posts reached over 20 million users. To date, CAPSTONE has provided opportunities for 17 mapping students through NOAA's Explorer-in-Training program, which helps to educate the next generation of ocean explorers.

## 2017 CAPSTONE Expeditions

The 2017 central Pacific expeditions will target efforts in the vicinity of the Hawaiian Archipelago, areas of the Pacific Remote Islands Marine National Monument, the National Marine Sanctuary of American Samoa, and the Rose Atoll Marine National Monument. While the focus of 2017 operations remains within US waters, NOAA has formed partnerships with several Pacific Island nations and territories to expand the CAPSTONE effort internationally to include the Phoenix Islands Protected Area located within the Republic of Kiribati, the Cook Islands, and New Zealand's Territory of Tokelau. NOAA is working with the Secretariat of the Pacific Regional Environment Programme and other partners to share CAPSTONE results with Pacific Island Nations invested in the Framework for a Pacific Oceanscape, designed to catalyze action in support of the Pacific Islands Regional Oceans Policy, and Big Ocean, a network of the world's large-scale marine managed areas.

*CAPSTONE has revealed the deep ocean for the first time in areas that are under the jurisdiction and management of US and insular agencies. This exploration provides scientists and resource managers with a broader view of the incredible diversity of geological features and marine life, as well as the foundational information society needs to begin to understand and address the complex and pressing issues related to the deep ocean.*

### *Okeanos Explorer* 2016 Expeditions

| | |
|---|---|
| 11 | Cruises |
| 17 | Vessel CTD casts |
| 553 | Submersible CTD casts |
| 486 | XBT casts |
| 69 | ROV dives |
| 96,391 km | Distance mapped |
| 277,662 $km^2$ | Area mapped |
| > 4.3 million | Views of the live video feeds |


The control room on *Okeanos Explorer* during the first dive of the Wake expedition.

A high-density coral community was encountered as the ROV proceeded up the slope of a pinnacle feature located on the crest at Swordfish Seamount, one of the Geologist Seamounts.

# 2016 Hohonu Moana: Exploring the Deep Waters off Hawai'i

By Daniel Wagner, Jonathan Tree, Brian R.C. Kennedy, and Kasey Cantwell

Papahānaumokuākea Marine National Monument (PMNM) is the only UNESCO World Heritage Site in the United States that is distinguished for both its natural and cultural resources. The PMNM is home to diverse ecosystems with myriad endangered and endemic species. On August 16, 2016, President Obama expanded PMNM from 362,073 $km^2$ to 1,508,870 $km^2$, thereby making it the largest conservation area on Earth at the time. The vast majority of PMNM lies in deep waters (>2,000 m) and had not been explored until recently.

In 2015, NOAA began CAPSTONE with four cruises that explored the deep waters in and around PMNM under the title "2015 Hohonu Moana: Exploring the Deep Waters off Hawai'i." Hohonu Moana means "deep ocean." Building upon the success of those expeditions, NOAA returned to the region in 2016 to explore deepwater habitats in some of the most remote portions of the PMNM. Although the primary objective was to conduct ROV surveys, bad weather hampered ROV operations throughout the 25-day cruise, leading the ship to focus instead on mapping operations while avoiding storms. Using NOAA Ship *Okeanos Explorer*'s nine high-resolution sonars, over 31,000 $km^2$ of ocean seafloor were mapped, including five seamounts that had not been previously examined (Figure 1). These seamounts now fall within the expanded boundaries of the monument and provide a foundation for future exploration of these habitats. When the weather was favorable, eight ROV dives, at depths ranging from 650 m to 4,300 m, were completed. Five of these dives were inside the old boundaries, and the remaining three were in areas now included in the recently expanded boundaries of PMNM.

## ROV Exploration

Most dive sites were selected to target volcanic seamount features, known as rift zone ridges, in order to address both biological and geological science objectives. From a biological perspective, rift zone ridges are important because their steep topography creates habitat for diverse and abundant biological communities (Figure 2). Geologically, rift zone ridges are the extinct focal points of prehistoric submarine eruptions and thus provide valuable information about the past. These features are built when magma is transported through the interior of the volcano and erupts at the surface. Over time, repetition of this volcanic cycle results in the construction of rift zone ridges. As these features build, both vertically and horizontally, they become a characteristic part of the volcano's overall geometry. These ridges then interact with local currents to create some environments with increased current flows where filter-feeding organisms like deep-sea corals and sponges thrive.

Figure 2. High-density aggregation of brisingid brittle stars documented at 650 m depth on an unnamed seamount west of Salmon Bank, in the area that was included in the recently expanded Papahānaumokuākea Marine National Monument.

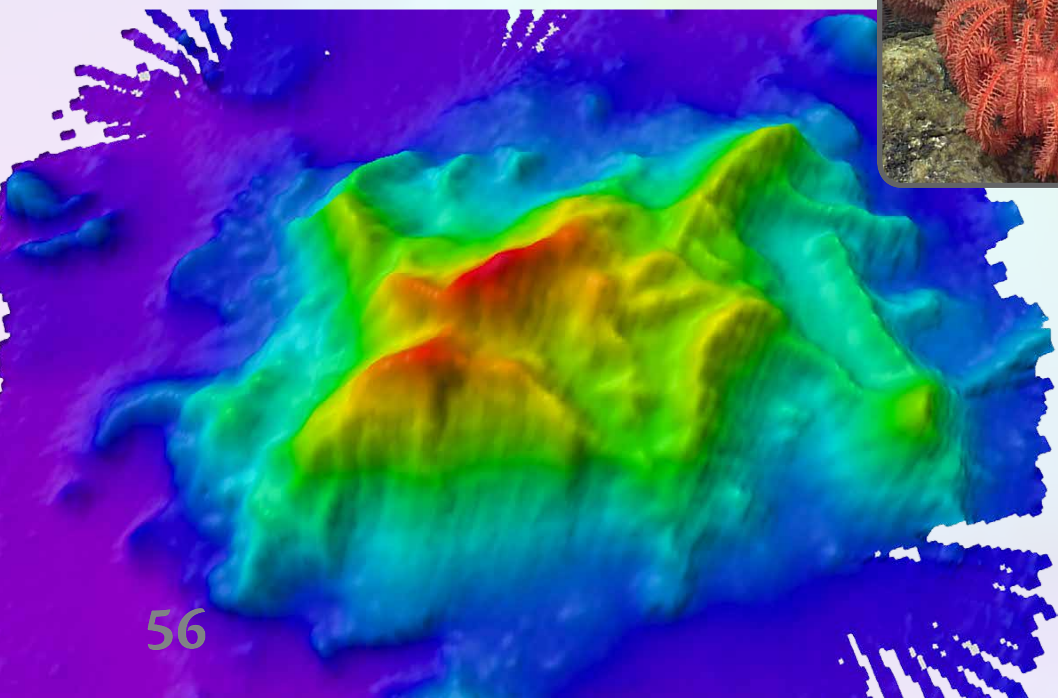


Figure 1. High-resolution bathymetric map of an unnamed seamount. This seamount was one of five mapped for the first time as part of the 2016 Hohonu Moana expedition.

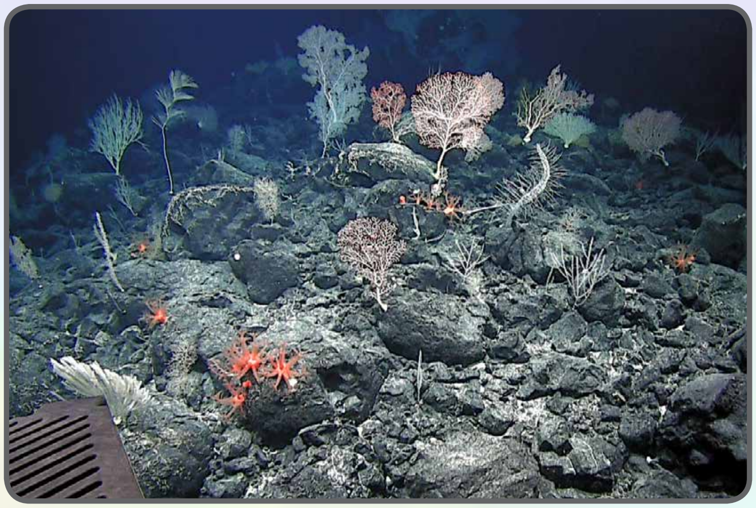


Figure 3. A diverse and high-density community of deep-sea corals and sponges documented by ROV *Deep Discoverer* at 2,019 m depth on Castellano Seamount.

Figure 4. An unidentified species of bamboo coral sampled by ROV *Deep Discoverer* at 842 m depth on an unnamed seamount west of Salmon Bank in the area that was included in the recently expanded Papahānaumokuākea Marine National Monument. This species is a new record for the Hawaiian Archipelago and likely a new species to science.

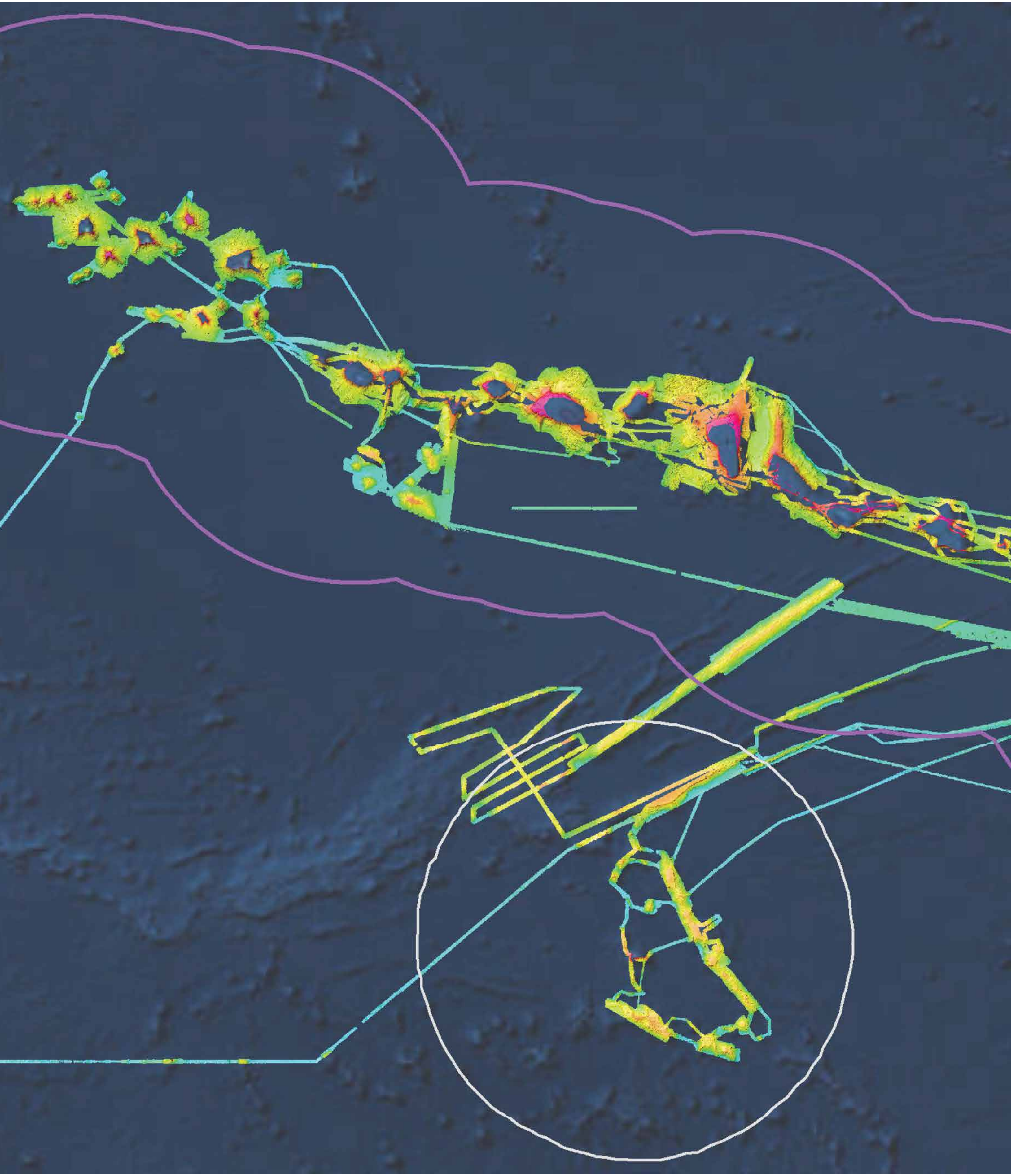
Figure 5. Incirrate octopus photographed at 4,292 m depth on a ridge located northeast of Mokumanamana Island. Besides being a new species, this octopus likely belongs to a new genus, and represents the deepest record in the suborder of incirrate octopuses.

One of the main CAPSTONE objectives for this cruise was to survey manganese-crusted, hard-bottom habitats and locate vulnerable biological communities, particularly high-density deep-sea coral and sponge communities (Figure 3). Five dives discovered high-density communities at depths between 650 m and 2,300 m (Figure 4), all on rift zone ridges or pinnacles, supporting the hypothesis that high-density communities form over steep topography. Four of the high-density communities were found in areas that had never before been explored. In contrast, the high-density community documented at Pioneer Bank Ridge was surveyed in 2003 by the Hawaiʻi Undersea Research Laboratory and in 2015 by *Okeanos Explorer*. During our 2016 dive, ROV *Deep Discoverer* explored locations directly below the known community in order to determine its lower depth limit. The survey revealed that the high-density community at Pioneer Bank Ridge extends for over 16 km at depths between 1,800 m and 2,350 m, now the largest such aggregation known from Hawaiʻi. Additionally, the expedition focused on documenting species that were not previously known in the region. A total of 249 species were identified from visual surveys. The majority of observed species have never before been described, including a new species of incirrate octopus that was documented at 4,292 m on the expedition's first dive (Figure 5). Furthermore, 13 biological specimens were collected, all representing either new species or records for Hawaiian waters.

## Building a Legacy of Science and Exploration in Support of Management

This expedition was the latest in a series of voyages to PMNM sponsored by NOAA's Office of Ocean Exploration and Research. In 2009, *Okeanos Explorer* was one of the first research vessels to map large areas in the deep waters of the Northwestern Hawaiian Islands. In 2015, NOAA returned to the area as part of CAPSTONE, this time equipped with its deepwater ROVs and telepresence technology, in addition to its high-resolution mapping systems. The expedition was a great success and generated the first images ever captured in the region at depths below 2,000 m.

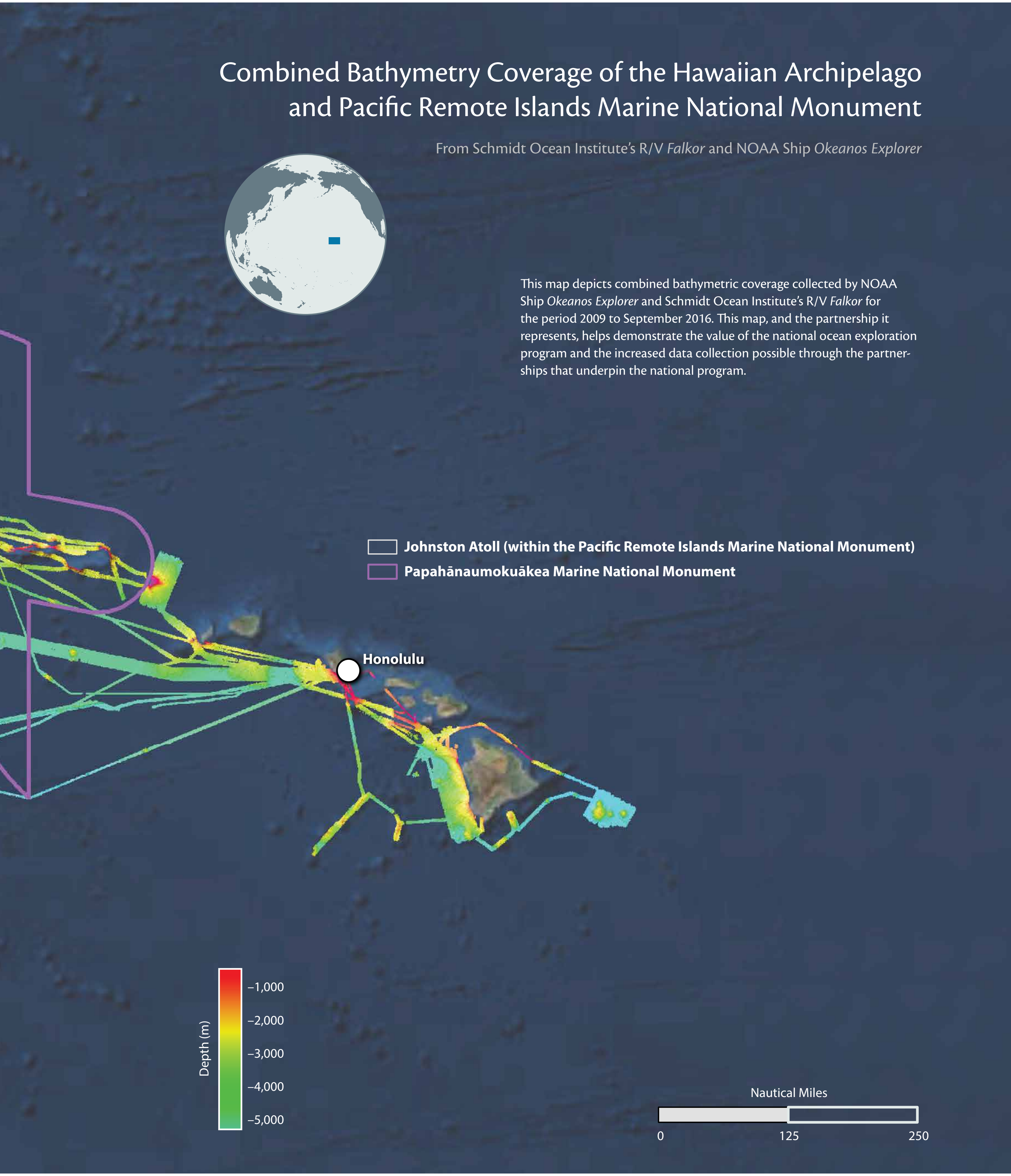
Collectively, *Okeanos Explorer* has completed 26 ROV dives to survey over 17 km of seafloor within the PMNM, collected over 60,000 km$^2$ of high-resolution multibeam bathymetry, identified 15 high-density biological communities, and documented dozens of new species or records. Hohonu Moana expedition results demonstrate that deep waters in the Northwestern Hawaiian Islands represent important reservoirs of biodiversity and provide scientific support for expansion of the monument. Furthermore, all data collected as part of this effort are publicly available, thereby supporting science, management, and conservation of deep-sea ecosystems by providing a repository of information that is widely accessible to resource managers, scientists, policymakers, economists, educators, and the public.



# Combined Bathymetry Coverage of the Hawaiian Archipelago and Pacific Remote Islands Marine National Monument

From Schmidt Ocean Institute's R/V *Falkor* and NOAA Ship *Okeanos Explorer*

This map depicts combined bathymetric coverage collected by NOAA Ship *Okeanos Explorer* and Schmidt Ocean Institute's R/V *Falkor* for the period 2009 to September 2016. This map, and the partnership it represents, helps demonstrate the value of the national ocean exploration program and the increased data collection possible through the partnerships that underpin the national program.



# Deepwater Exploration of the Marianas

By Diva J. Amon, Patricia Fryer, Deborah Glickson, Shirley A. Pomponi, Elizabeth Lobecker, Kasey Cantwell, Kelley Elliott, Derek Sowers, and the NOAA Ship *Okeanos Explorer* EX1605 Expedition Team

The most well-recognized area of the Mariana region is undoubtedly Challenger Deep, the deepest point in our ocean at over 10,900 m. As a result, most Mariana deep-sea research has been focused on this tiny spot in the subduction zone's trench or in the volcanic back arc; however, much of the deepwater habitats of this diverse and dynamic region remain poorly understood.

As part of the CAPSTONE effort, NOAA and partners conducted the Deepwater Exploration of the Marianas expedition on NOAA Ship *Okeanos Explorer*. The primary goal of this three-leg, 59-day expedition was to collect baseline biological and geological information from a variety of deepwater habitats in and around the Marianas Trench Marine National Monument (MTMNM), Guam, and the Commonwealth of the Northern Mariana Islands (CNMI). Baseline characterizations expand our understanding of the diversity and distribution of benthic and pelagic habitats, as well as their geologic underpinnings, and contribute to better management of this unique environment.

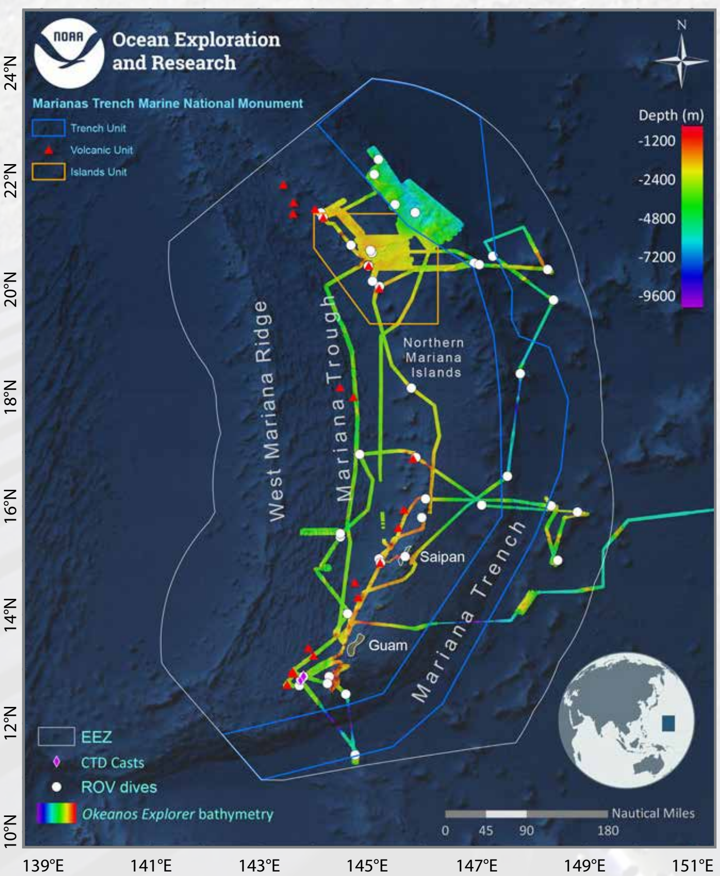



Figure 1. 2016 Deepwater Exploration of the Marianas expedition map.

Prior to commencing the expedition, science priorities were identified through interactions between NOAA, CNMI, and MTMNM managers, and the science community. This planning process identified several key exploration objectives to address current knowledge gaps in the region: (1) locating and assessing commercial bottomfish and precious coral habitats; (2) identifying vulnerable marine habitats, particularly high-density deep-sea coral and sponge communities; (3) surveying the communities that exist on ferromanganese-encrusted guyots; (4) mapping and conducting ROV transects over a variety of geologic structures within the region, including hydrothermal vents, volcanic areas, and ridges; (5) investigating subduction zone areas and the habitats within the abyssal-hadal transition zone of the trench; (6) exploring life in the water column; and (7) searching for submerged cultural heritage sites in an area that played a critical role in World War II. Operations were designed to target these priorities during 41 ROV dives that ranged from 240 m to 6,000 m depth, including 18 within the MTMNM, and the equivalent of ~35 days of mapping over 73,800 km$^2$ of seafloor (Figure 1). During ROV dives, 58 biological samples (plus 102 commensals) were collected, many of which may be undescribed species, and 73 rock samples were collected for use in age dating and geochemical composition analysis. The expedition accumulated more than 48 terabytes of data that include video and still imagery, multibeam sonar and single-beam echosounder recordings, subbottom profiles, current profiles, CTD and dissolved-oxygen measurements, and surface oceanographic and meteorological information.

## Exploration for Commercial Species and High-Density Biological Communities

To address fisheries priorities identified by expedition partners, 12 ROV dives targeted depths where bottomfish and precious corals exist. A number of commercially viable bottomfish species were observed, including pale snapper (*Etelis radiosus*), deepwater longtail red snapper (*E. coruscans*), deepwater red snapper (*E. carbunculus*), eightbar grouper (*Hyporthodus octofasciatus*), amberjack (*Seriola* sp.), dogtooth tuna (*Gymnosarda unicolor*), monchong or sickle pomfret (*Taractichthys steindachneri*), roughy (*Hoplostethus* sp.), oblique-banded snapper (*Pristipomoides zonatus*), ornate jobfish (*P. argyrogrammicus*), goldflag jobfish (*P. auricilla*), and golden grouper (*Saloptia powelli*). Despite precious coral being listed as a managed fishery in Guam and the CNMI, no

Figure 3. Vogt Seamount hosted one of the most diverse and dense communities of deep-sea corals and sponges of the entire expedition. Colonies were very large—several over a meter in height or width—indicating healthy and stable communities.

Figure 2. The Deepwater Exploration of the Marianas expedition successfully confirmed the presence of precious corals throughout the region with the first-ever in situ imagery of these organisms. This gold coral was spotted on the ROV dive at the Santa Rosa North site. Red dots in the images are 10 cm lasers used for scale.

Figure 4. ROV *Deep Discoverer* collects one of the many gorgonocephalid basket stars spotted at Zealandia Bank.

precious coral beds had been identified prior to this expedition, and accounts of their presence in this region were only anecdotal. The search for precious corals was successful with observations of *Corallium* spp., *Hemicorallium* spp., *Leiopathes* spp., *Acanella* spp., and *Kulamanamana* sp. (Figure 2), although there were fewer than expected. There appeared to be little overlap between bottomfish and precious coral habitats, as bottomfish were found at shallower depths, though there was overlap between bottomfish and non-precious coral habitat.

Aside from documenting precious corals, this expedition was the first to specifically explore for deep-sea coral and sponge communities in the Mariana region. Ten high-density and several medium-density communities were identified. Many of them were highly diverse and included corals such as primnoids, isidids, chrysogorgiids, paragorgiids, stylasterids, desmophyllids, and plexaurids, as well as a combination of hexactinellid and demosponge sponges. Some of the corals and sponges, especially at Vogt Seamount, were very large (over one meter in width) indicating healthy and stable communities (Figure 3). These high-density communities are extremely important; as in shallow coral reefs, they provide habitat and shelter to many different animals (e.g., commensal echinoderms and crustaceans, and also commercial fish species). A notable rare find never before observed in the Mariana region was a high-density community of gorgonocephalid basket stars and stalked crinoids at Zealandia Bank (Figure 4).

## Volcanically Active Areas

As part of this expedition, three hydrothermal vent sites were characterized for the first time. The most spectacular was an active vent field on the Mariana back-arc spreading center, imaged for the first time since its discovery by the NOAA Pacific Marine Environmental Laboratory's Vents Program in 2015. There were at least two large chimney sites, plus multiple areas of diffuse flow, and a circular crater (origin as yet undetermined) surrounded by sulfide deposits. A 30 m tall black smoker discovered at 3,292 m depth emitted fluid at 339°C and hosted large communities of *Chorocaris* shrimp, *Gandalfus* crabs, actiniarians, barnacles, *Bathymodiolus* mussels, *Alviniconcha* snails, *Paralvinella* tubeworms, and many other species known from other active sites in the region (Kojima and Watanabe, 2015; Figure 5). The fauna showed clear zonation consistent with distance from the vent fluids. A second new vent field was discovered at approximately 980 m depth on Chamorro Seamount, an area with no known history of hydrothermal activity. Chimneys were 1–2 m tall, with fluid temperatures as high as 31°C, and were dominated by stylasterid corals, *Alvinoconcha* snails, *Chorocaris* shrimp, and *Gandalfus* crabs. Other fauna documented included amphipods, polychelid lobsters, unidentified demosponges, synaphobranchids, and macrourids. New areas of hydrothermal

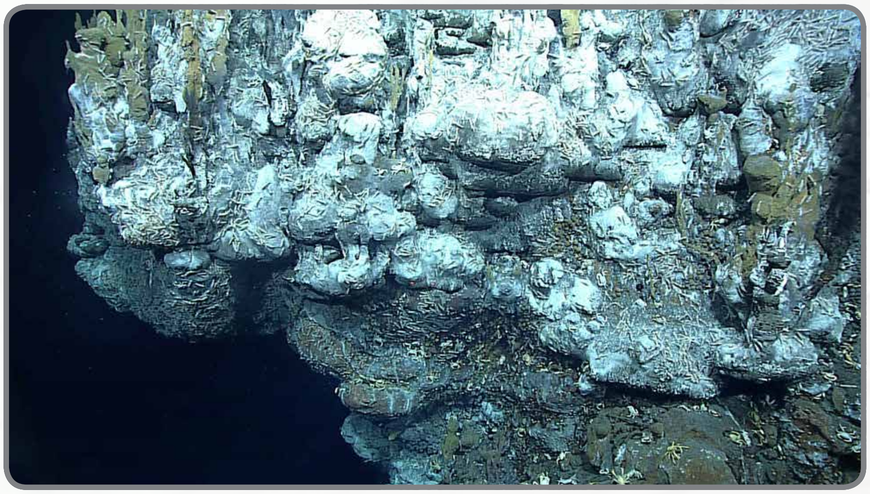
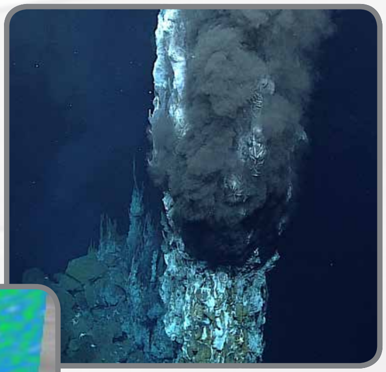


Figure 5. Fauna colonizing the black smokers included a number of animals common to hydrothermal vents in the region—*Chorocaris* shrimp, *Gandalfus* crabs, and *Alviniconcha* snails.



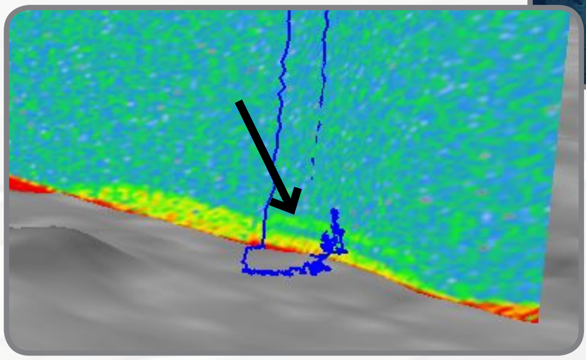


Figure 6. (left) Simrad EK60 water-column data show acoustic evidence of hydrothermal vent activity as a yellow "cloud" near the seafloor where a black smoker (above) was discovered during ROV dive 11 (dark blue track line).

activity were also discovered on the southeast side of Eifuku Seamount, with much of the area exhibiting diffuse low-level hydrothermal activity at temperatures reaching 16°C.

Dives were also conducted at Ahyi Seamount, at Daikoku Seamount, at an area of fresh lava flows in order to document change in areas with evidence of recent eruptions, and at extinct calderas (Fina Nagu volcanic chain) in order to evaluate the geologic progression of volcanic activity. The seafloor and slope of Daikoku Seamount were covered with volcanic ash and volcaniclastics. Many tubeworms, barnacles, and anemones were also observed, as well as a high density of flatfish specialized for living on the sulfur-rich seafloor. Gas plumes of likely carbon dioxide and sulfur were emanating from cracks and orifices near the crater rim and along the lower wall of the crater. Very few sessile animals were observed at Ahyi Seamount, and it was speculated that recent volcanic activity might be the cause. Recent lava flows, including some that were less than two years old (as indicated by bathymetric surveys and ROV images) were observed at a site known as "Young Lava Flows." This site also had very little faunal colonization, as the basalt was likely too new. There were also extinct hydrothermal chimneys noted at Fina Nagu A and extinct iron-oxide chimneys in Esmeralda Crater.

## Acoustic Mapping

In pursuit of the NOAA OER strategic objective to collect modern sonar data over previously unmapped or poorly mapped areas of seafloor, acoustic mapping operations focused on the northernmost section of the MTMNM Island and Trench Units, in priority areas identified by expedition partners, and were also conducted during transits between ROV dive sites. Execution of this plan resulted in collection of 60 m resolution (or better) bathymetric data over several key features, including complex folded ridges, a crescent ridge, mud volcanoes, sites of hydrothermal venting, and the definition of the 6,000 m isobath on the west side of the trench. Additionally, a large volume of split-beam, subbottom, and ADCP sonar data was collected and deposited in the national data archives.

ROV dive plans were refined based on the high-resolution bathymetric data collected, and in some cases, dives revealed correlations between anomalies observed in acoustic water-column data and hydrothermal venting. At the site called "New Vent Field at 17°N," a dive to 3,292 m depth on a relatively flat area of the Mariana back-arc spreading center located several high-temperature black smokers. Simrad EK60 split-beam data collected at this site showed a distinct water-column anomaly likely associated with the venting activity, which was observed over several hundred meters of seafloor during the dive (Figure 6). The dive at Esmeralda Crater within the MTMNM, another site with previous evidence of hydrothermal venting, was conducted in relatively shallow water (~350 m; Figure 7). While only a single extinct chimney was found by the ROV during the dive, several strong persistent scattering layers were repeatedly detected with multiple EK60 frequencies. The acoustic scattering layers could be due to the chemical, physical, and thermal composition of the particulate-laden fluid emitted during venting, or to biomass associated with the vent communities.

The initial findings from these two dives demonstrate the potential for use of acoustic split-beam data, when interpreted within the local geological context, to determine the presence and extent of vent fields. Use of this technique may increase the ability and efficiency of detecting hydrothermal vents, and would complement traditional chemical-sensing methods such as CTDs. Additionally, because split-beam echosounders can be calibrated for acoustic target strength, there is potential for these data to provide insights into flux rates of gas and particulates emanating from vents, a complex phenomenon whose study currently requires direct measurements with ROVs.

## Forearc Exploration

The forearc region, from the trench axis westward to the active island-arc volcanoes, contains the oldest rocks (~52 million years) in the region and tells the history of subduction in the Mariana Trench. ROV imagery and multibeam mapping from this expedition provide improved geologic context for the forearc region, which includes extensive and complex faulting. Mapping operations identified several new features, including a crescent-shaped ridge along the western wall of the Mariana Trench (not evident in satellite altimetry), several potential mud volcanoes, and a ridge with tiered platforms that was anecdotally named "Explorer Ridge." Two subsequent ROV dives conducted at Explorer Ridge revealed a large coral community and documented the first-ever live sighting of a fish from the family Aphyonidae (ghost fish). It was observed at a depth of ~2,500 m, was about 10 cm in length, and had transparent gelatinous skin that lacked scales and had highly reduced, unpigmented eyes (Figure 8).

The eastern half of the Mariana forearc is host to numerous mud volcanoes that have been periodically erupting since subduction began. As the Pacific Plate descends into the subduction zone, increases in pressure and temperature squeeze out fluids from the sediments and rocks being subducted. These fluids rise into the overriding Philippine Sea Plate and hydrate rocks within its many forearc fault zones. Particularly where faults intersect, the fluids can find escape routes to the seafloor. Because fluids rise along the faults, any rock material ground up by movement within the fault zones can be remobilized. The hydrated material is less dense than surrounding rock and tends to rise with the fluids in a slurry of "mud" (Fryer, 2012). Two of the potential mud volcanoes mapped during this expedition were confirmed during ROV dives through collection of imagery and serpentinite samples. Serpentinite is a product of the hydration of mantle rock (peridotite) and comprises >90% of a mud volcano. No active seepage (typically associated with mud volcanoes) was found on the crest of either the Kunanaf Hulo mud volcano or the "unnamed forearc mud volcano." Instead, sedimented seafloor inhabited by deposit feeders was observed. Also, several suspension-feeding sponges with *Relicanthus* sp. (a cnidarian similar to an anemone) living on their stalks were documented, an association rarely seen, but common among those observed (Figure 9).

Figure 9. This *Relicanthus* sp., a cnidarian resembling a sea anemone, was seen on an unnamed forearc seamount in the northern part of the Trench Unit of MTMNM.

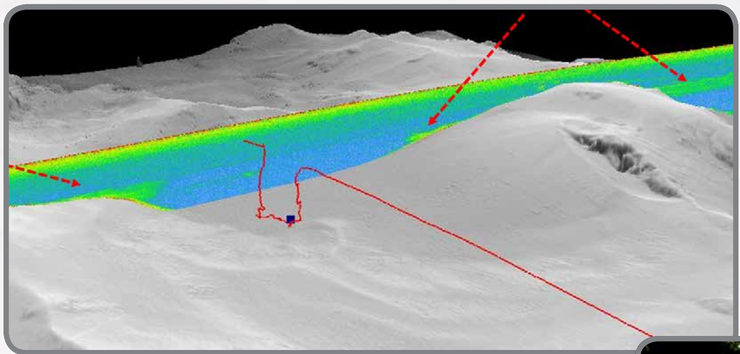


Figure 7. Simrad EK60 water-column data shows acoustic evidence for potential hydrothermal vent activity as green "clouds" in the Esmeralda Bank crater. The trackline of an ROV dive there is shown in red, and the dark blue point marks the location of an extinct chimney discovered during the dive.

Figure 8. This "ghost fish" is the first specimen from the family Aphyonidae ever seen alive. Observed on "Explorer Ridge" at a depth of ~2,500 m, the 10 cm long fish had transparent, gelatinous skin that lacked scales and had highly reduced eyes without pigment.

## Exploration of the Mariana Trench and Subducting Areas

Nine dives were conducted along the west slope of the trench and an additional three along the trench axis or within the MTMNM Trench Unit. Because the Mariana Trench lacks a thick wedge of sediment off-scraped from the subducting plate or derived from nearby land masses, Earth's upper mantle is exposed at depths near 6 km. Three dives to 6,000 m examined the deep architecture of the overriding Philippine Sea Plate near the trench axis (Figure 10) and cataloged the diversity of organisms at the hadal-abyssal transition zones. A high diversity of species was observed—including many potential new species or new records. Several species of holothurians, crinoids, swimming polychaetes, enteropneusts, cladorhizid sponges, brisingid asteroids, and actiniarians were observed. Most fish observed in the trench were ophidiid cusk eels, including a *Penopus* sp. seen over 1,000 m deeper than previously recorded for the genus. A bamboo coral (Isididae) observed during the dive at "Subducting Guyot 2" at a depth of 4,300 m expanded the known depth range for this family by approximately 100 m, making it the deepest known Isidid ever observed.

At Sirena Canyon, baseline information was collected on the abyssal fauna, starting in a fault-controlled canyon south of Guam at ~5,000 m depth on a steep slope that exposed fractured, partially sedimented, volcanic rock below a layered sediment sequence. This supports the hypothesis that canyons act as funnels to the deep sea, enabling accumulation of high concentrations of organic material. This was also shown to be true of marine debris, with many pieces of trash observed at this site.

Just inside the MTMNM boundaries, west of Fryer Guyot, a dive was conducted on a small (1 km in diameter and 141 m in height) volcanic edifice—a potential petit-spot volcano—to determine if it was located on a fracture in the Pacific Plate that formed prior to subduction. This type of young intraplate volcano was previously discovered east of the Japan Trench (Hirano et al., 2008). In addition to documenting this for the first time in US waters, the dive helped to determine that such occurrences might be a common feature of subducting plates as they fracture while bending.

## Cretaceous Guyots

Five dives took place on Pacific Plate guyots—large, flat-topped, submarine volcanoes that formed 80 to 100 million years ago. Because of their age, these guyots have thick crusts of economically valuable metal oxides that are potential sources of cobalt, copper, manganese, platinum, and other metals (Figure 11). The guyots visited (Vogt, Pigafetta, Del Cano, Fryer, and Enrique) are located in the Prime Crust Zone, the region with the most valuable, and therefore the most vulnerable, ferromanganese crusts on the planet (Hein, 2004). In international waters east of the CNMI, three exploratory mining licenses have been granted at present. The guyots investigated can be used as proxies to better understand habitats in international waters that are vulnerable to deep-sea mining. The ROV dives highlighted a high diversity of both geology and biology at each location, suggesting that guyots can host a range of communities and may need to be considered individually, versus as a group, from a management perspective. However, only a small area of each guyot was surveyed, so broad conclusions cannot yet be drawn.

Three additional unnamed Pacific Plate guyots were also explored. These guyots are being subducted beneath the Philippine Sea Plate and have "broken open" to reveal their underlying structures. The edge of Subducting Guyot 1 can still be seen on the inner trench slope as it burrows its way under the edge of the overriding Philippine Sea Plate, exposing fossil reef-building rudist bivalves (Figure 12) along near-vertical fault scarps. Rudists dominated the seas 65 to 100 million years ago, and this was the first time they were observed in today's ocean.

Figure 10. ROV *Deep Discoverer* explores at a depth of 6,000 m in the Mariana Trench. Never-before-seen geological features reminiscent of the Alps and canyons in California stunned participating scientists on the ship and on shore.

Figure 11. The substrate at Fryer Guyot, covered with a ferromanganese crust, is typical of guyots observed during the expedition.

## Expedition Highlights

Hundreds of different species were observed during the ROV surveys, including sponges, molluscs, tunicates, ctenophores, fishes, bryozoans, cnidarians, echinoderms, and arthropods (Figure 13). Dozens that were not collected were suspected to be new species, including several species of jellyfish, a nudibranch, a slit shell gastropod (a living fossil; Figure 14), holothurians, cladorhizid (carnivorous) sponges, and an electric-blue tilefish. Several new species of hexactinellid sponges were also observed. Additionally, there were new range and depth records for the Mariana region. These included the first records for the region of the family Ateleopodidae (jellynose eels), a slit shell gastropod (cf. *Bayerotrochus teramachii*), a gorgonocephalid basket star, several cusk eels, a large blind lobster (*Acanthocaris tenuimana*), two nudibranchs, and *Relicanthus* sp. Even if an organism was not a new species, new record, or rare, many were still extremely strange—from the numerous walking fishes to candelabra-shaped carnivorous sponges and hermit crabs with actinarians replacing their shells.

Other highlights included locating a B-29 Superfortress long-range heavy bomber from World War II in the channel between Tinian and Saipan (see pages 72–73). This expedition also featured the deepest ever (4,000 m) water-column exploration and spent a significant portion of four dives collecting critical information in this vast biome (see pages 66–67). The majority of organisms identified during these transects were new records for the Mariana region, rare observations, or potential new species, indicating an active, but largely unknown pelagic community.

This expedition also set several records for an OER telepresence-enabled expedition. Throughout the three cruises, 100 shoreside scientists, student researchers, and managers participated, with the science team representing 16 US states and six foreign countries. Around the world, members of the general public watched as the expedition unfolded in real time. The live video feeds received a record-breaking 3.1 million views, which stands as a testament to the public's interest in learning about and exploring the deep sea. This was one of the longest ROV missions that *Okeanos Explorer* has ever undertaken, and the value of the work completed leaves a legacy of publicly available data that will be used to catalyze future research efforts and inform management decisions.

Figure 12. One of the many rudist fossils observed at Subducting Guyot 1 while exploring a crack caused by subduction pressure. This was the first time rudists had been observed in the ocean.

Figure 13. Throughout the dive at Farallon de Medinilla, several coral colonies, like this bubblegum coral, were entangled with unidentified green filaments. The expedition science team was perplexed by the filaments, as plants are generally not found at these depths (492–533 m) due to the lack of light. The standing hypothesis is that they are sponges or possibly algae that drifted down from the surface and snagged on the coral.

Figure 14. An exciting discovery during a dive at Pagan, this slit shell snail was a new observation for the Marianas and likely a new species.

# The 2016 Midwater Exploration of the Mariana Region

By Mike Ford and Amanda Netburn

The midwater, which lies between the upper ocean and near-bottom layers of water, represents possibly the largest biome on Earth. Despite its vast expanse, the midwater remains one of the most poorly explored regions in the global ocean, especially in remote parts such as the Mariana Islands. The 2016 Deepwater Exploration of the Marianas segment of CAPSTONE explored the midwater in this critical region (Figure 1). At four sites, participating scientists investigated water masses above seamounts (Figures 2 and 3) and at an active hydrothermal vent to develop the first characterizations of each of these sites.

## Maug Volcano

The water column surrounding Maug Volcano is protected within the Marianas Trench Marine National Monument. Midwater ROV exploration there was the first at this location. The team encountered numerous chaetognaths, a solitary salp, a polychaete (Tomopteridae), and two siphonophores: a physonect (Physonectae) and a calycophoran (Calycophorae). Several copepods were visible with the high-definition cameras.

In addition to these fauna, the team observed several cestid ctenophores (Phylum Ctenophora: Class Tentaculata: Order Cestida). Along the trailing edge of this unusual ctenophore's wing-like body are two ctene rows. Both propulsion modes known for these ctenophores—the typical slow propulsion mode and the faster escape propulsion mode—were on display (Matsumoto, 1991; Stretch, 1982). In the slow propulsion mode, rows of fused cilia pulse to produce horizontal movement with the animal oriented so that the mouth is at the leading edge of the body—like an airplane wing gliding through the air. In the escape response, the entire body undulates to achieve movement along the long axis of the body.

While the primary objective was to discover what midwater fauna were present, the team glimpsed some aspects of the trophic ecology in this system. For example, Cestid ctenophores suggest the presence of small copepods (Haddock, 2007). The presence of chaetognaths supports the potential for copepod prey. As we explore the midwater biome, the development of an ecological understanding emerges as a future goal.

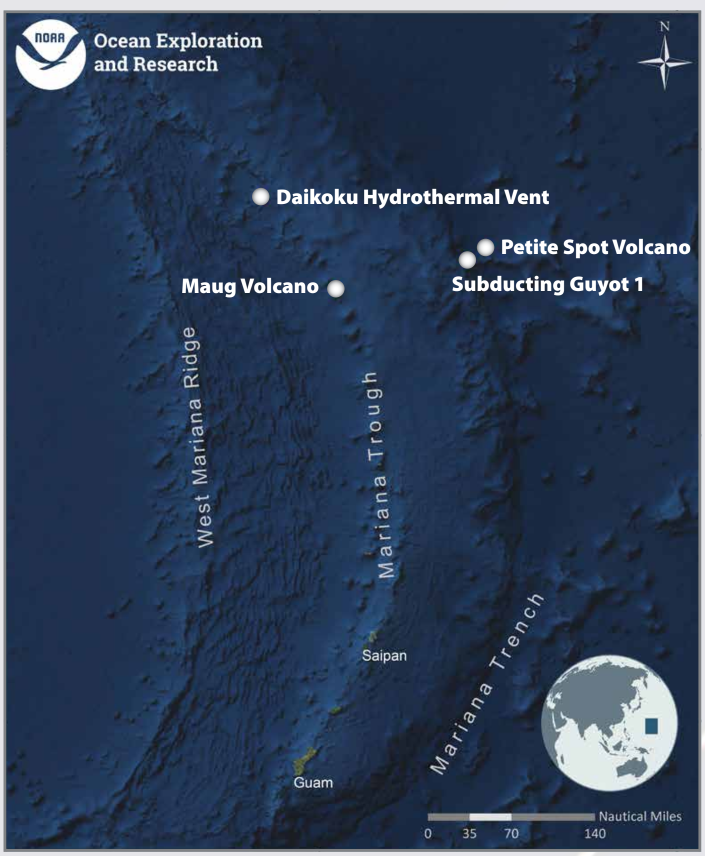



Figure 1. Exploration of the midwater was conducted at four dive sites during the 2016 Deepwater Exploration of the Marianas segment of CAPSTONE.

Figure 2. A pelagic worm encountered at Subducting Guyot 1 at 1,000 m, during a 4,000 m midwater survey.

Figure 3. Though small, chaetognaths (arrow-worms), such as the one imaged here, are major predators in the planktonic world. The imaging capabilities of ROV *Deep Discover* provide scientists with unparalleled opportunity to see animals such as these alive at such high resolution.

## Petite-Spot Volcano and Subducting Guyot 1

The fauna near Maug Volcano, over a petite-spot volcano, and Subducting Guyot 1 indicated diverse midwater communities. Numerous medusae were observed during the two dives, including coronate scyphomedusae, narcomedusae, and hydromedusae (Figures 4 and 5). It was interesting that an assortment of body forms, and their associated foraging strategies, were found within the limited volume of these dives. Some observations suggest an ambush foraging mode, while other species observed suggest predation while on the move. The different types of gelatinous animals give us a sense of the potential complexity of the food web dynamics that might be occurring in these little-known habitats.

## Daikoku Hydrothermal Vent

The objective of the midwater portion of the Daikoku hydrothermal vent dive site was to explore the water column macrofauna associated with the vent plume. Little is known about the associations between hydrothermal fluids and pelagic animals (Levin et al., 2016). We were interested to see if there was any evidence of an association (or avoidance) of animals either within or at the edge of the Daikoku plume, which extended from the seafloor at 408 m to approximately 350 m depth. We conducted short (10–15 m) vertically stacked transects through the plume at nine depths, from 2 m to 275 m above the seafloor. Turbulence and particulate concentrations were high within the plume. There was almost no visible life within this plume, and we speculate that this could be a result of either high turbulence or toxicity of hydrothermal vent fluids and/or associated particles. In contrast, numerous organisms were observed at the plume's edge, including salps, siphonophores, chaetognaths, and larvaceans (Burd and Thomson, 1994). An abundant amphipod aggregation coincided with a peak in acoustic backscatter observed with the ship's Simrad EK60 echosounder. Understanding the role of the hydrothermal vents on surrounding productivity is essential to understanding the ecosystem of protected regions such as the Marianas Trench Marine National Monument.

## Conclusion

At each of the dives sites, nature presented interesting and diverse assemblages of organisms. In some instances, the ROV dives returned the first images of this realm. Future dives will build on our understanding of ocean ecology, systematics, and the connections between the environment and these unique systems.

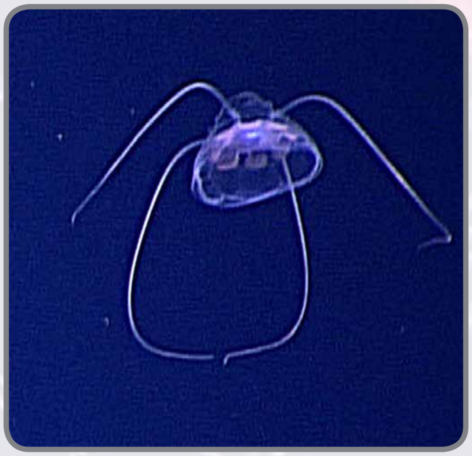


Figure 4. A narcomedusa in the midwater near the petite-spot volcano. These tentacles can extend above the top of the bell as well as trail behind the bell during movement.

Figure 6. Wispy appendages provide a sensory function for this glowing sergestid shrimp seen swimming in the water column over a petite-spot volcano in Marianas Trench Marine National Monument.

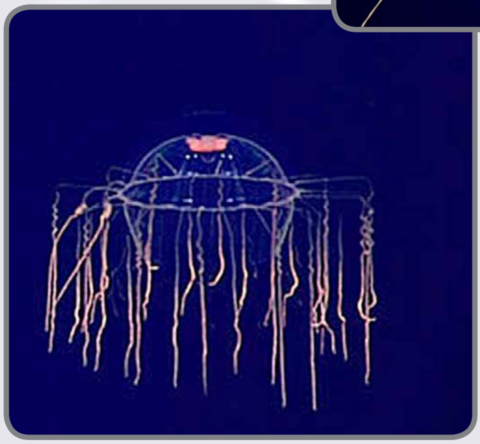


Figure 5. This hydromedusa was seen during exploration of the midwater near the petite-spot volcano with tentacles hanging in anticipation of prey encounter.

# First Deep Exploration in the Wake Unit of the Pacific Remote Islands Marine National Monument

By Christopher Kelley, Jasper Konter, and Brian R.C. Kennedy

The Pacific Remote Islands Marine National Monument (PRIMNM), established by President George W. Bush in 2009, is composed of five "units" located in the Central Pacific. In 2014, President Barack Obama expanded three of the five units, including the one encompassing Wake Island. One of the reasons for the expansion of the Wake unit was its location, roughly halfway between Hawaiʻi and the Marianas, in a large area of ocean known as the Prime Crust Zone (PCZ). The PCZ is considered to have the world's most economically valuable mineral-rich ferromanganese crusts, which coat most exposed rock in 1,000–2,500 m depths. Deep-sea mining of certain minerals in the PCZ could impact the environment. Submersible and ROV surveys have revealed the presence of significant deep-sea coral and sponge communities at crust mining depths in the Hawaiian Archipelago (Schlacher et al., 2013; Kelley et al., 2016). However, no similar types of surveys have ever been conducted in this part of the Pacific.

Only a handful of prior deepwater survey cruises had been conducted around Wake, and they only involved mapping around the island itself and limited mapping and dredging of seamounts north and west of the island (Winterer et al., 1993). None of these surveys involved biologic investigations and, as a result, our understanding of the deepwater biology around Wake was nonexistent. Our understanding of the monument's seafloor topography was largely derived from satellite altimetry, and its geology and geologic history were based mostly on interpolation of observations and rock samples from the entire western Pacific. On the most simplistic scale, the geology of the Wake monument unit can be described by three major components: (1) the island, (2) the seamounts around the island, and (3) the underlying seafloor. The latter is some of the oldest seafloor in the Pacific Ocean, and indeed the world, reaching an age of approximately 170 million years, as derived from seafloor magnetic anomalies (Müller et al., 2008; Figure 1). The island and the seamounts are thought to have originated between about 90 and 100 million years ago, based on age trends of similar seamounts outside of the monument (e.g., Winterer et al., 1993; Koppers et al., 2003).

Given its remote location and consequently the limited amount of previous deepwater work that had been performed there, the Wake monument unit of the PRIMNM presented a "first deep exploration" opportunity. Therefore, the 2016 *Okeanos Explorer* expeditions included three cruises around Wake. The first cruise, Mapping in the Pacific Remote Islands Marine National Monument, involved mapping operations only and took place from March 23 to April 13, 2016. This cruise departed from Kwajalein Atoll and transited north to the Wake monument unit, where it spent a total of 11 days, before it left the monument area and transited to Guam, where the cruise ended. During this cruise, all three of the ship's sonars—Kongsberg EM 302 multibeam sonar, Knudsen subbottom sonar, and Simrad EK60 split-beam fisheries sonar—were used to collect data around the clock. The multibeam and subbottom data were of particular importance for planning the subsequent cruises. The second cruise, Deepwater Wonders of Wake: Exploring the Pacific Remote Islands Marine National Monument, was primarily an ROV cruise—mapping operations only took place at night or during transits. This cruise departed Guam on July 28, and there was an ROV dive on July 30 in international waters on Alba (sometimes reported as Vlinder) Seamount. The cruise then

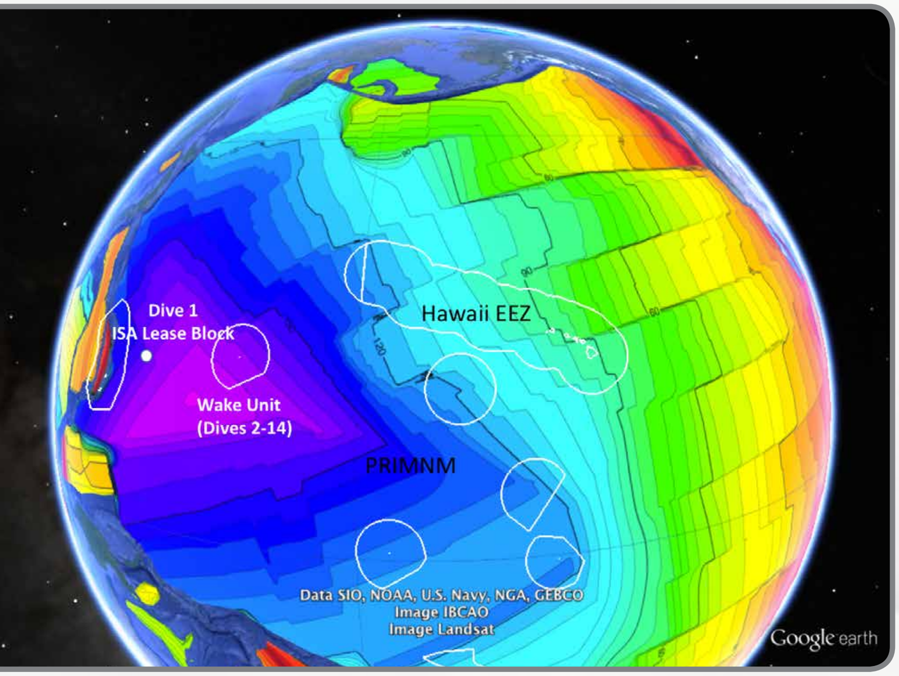



Figure 1. Map of the Pacific showing the estimated ages of the seafloor (red is youngest and purple is oldest). White lines encircle the various US monuments in the Pacific. *After Müller et al. (2008)*

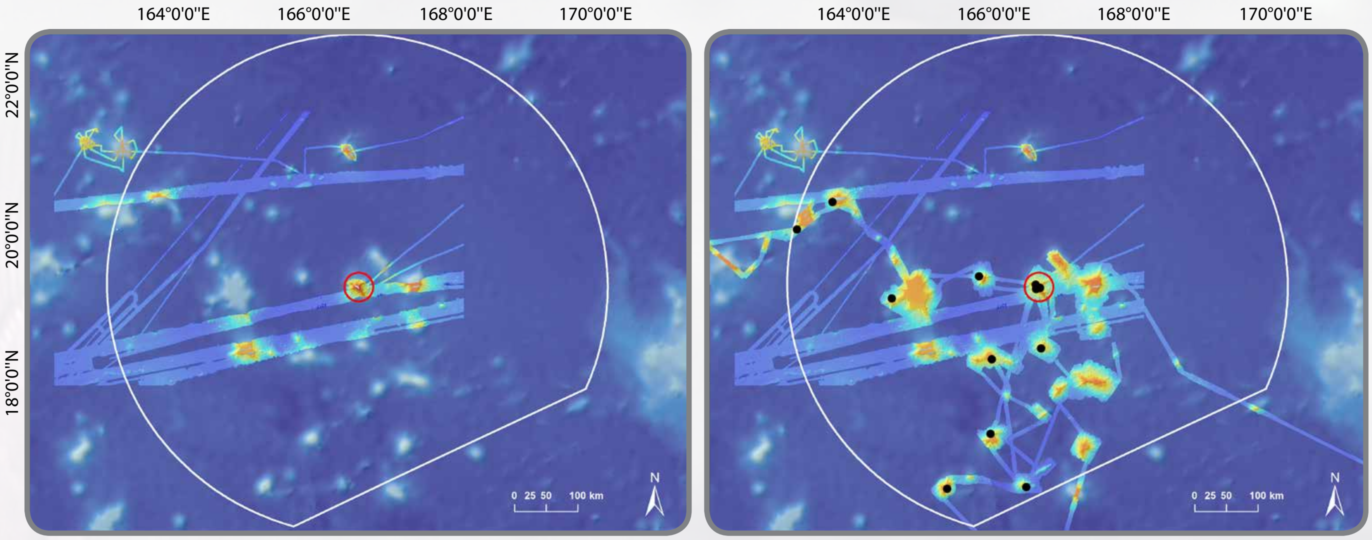



Figure 2. Extent of multibeam mapping done prior to (left) and after (right) the cruises described here. Black dots indicate the locations of dives 2–14 inside the Pacific Remote Islands Marine National Monument.

continued toward the next dive target located just inside of the northwest boundary of the Wake monument unit, arriving on site on August 1. From August 2 through 16, 13 dives were conducted inside the monument boundaries before the ship departed for Kwajalein Atoll, where the cruise ended on August 19. The third cruise, Telepresence Seafloor Mapping in the Pacific Remote Islands Marine National Monument – Wake Island Unit, was a mapping-only cruise. This last cruise departed Kwajalein Atoll, and transited back up to the Wake unit where it spent five days before departing for Honolulu on September 1. Below is a summary of the data acquired and the findings from these three cruises.

## Summary of Mapping Data

Multibeam coverage of the Wake monument unit was significantly increased during the cruises to this region (Figure 2). Examination of older satellite altimetry and the new multibeam data indicates that the Wake unit encloses one island (Wake Island itself) and 44 seamounts, 21 of which are small conical volcanoes and 23 of which are larger guyots (flat-topped seamounts). Prior to the cruise Mapping in the Pacific Remote Islands Marine National Monument, the slope of the island and at least some of the topography of nine of these seamounts (five cones and four guyots) had been revealed by data collected during previous cruises. Mapping conducted during the three 2016 *Okeanos Explorer* cruises revealed the topography on another 26 seamounts (nine cones and 17 guyots), leaving only nine completely unmapped seamounts. Satellite altimetry data suggest that seven of these are small cones and two are very small guyots. A single future cruise should be able to map these seamounts and complete a few "touch up" swaths on other seamounts to finish the mapping of all significant topographic features inside this monument unit.

## Summary of Geological Findings

The western Pacific hosts many Cretaceous-age guyots (Menard, 1964) that were formed in the currently volcanically active south-central Pacific Ocean (McNutt and Fischer, 1987; Davis et al., 1989; Larson, 1991; Staudigel et al., 1991; Janney and Castillo, 1999; Koppers et al., 2003; Konter et al., 2008). Guyots are commonly capped with coral reefs and pelagic sediments. However, seamounts west of Wake Island lack such a sediment cap (Winterer et al., 1993). The lack of reef cover on these seamounts is surprising, given their locations near the equator (Winterer et al., 1993). Instead of carbonate, the summits of these guyots host volcanic cones that postdate platform erosion; they erupted after the main volcanic structure was built, similar to post-erosional volcanism in Hawaiʻi (e.g., Winterer et al., 1993; Koppers et al., 2003). Mapping and ROV dives now provide new details on these guyots.

Most of the guyots are star shaped and have deep rift zones and a central shallow platform; some are connected by a rift zone (Figure 2). The summit platforms of the seamounts occur at three distinct depth ranges: (1) Wake Island at current sea level, (2) the majority of seamounts at ~1,400 m, and (3) one guyot at ~2,200 m. The three depth ranges define different platform-to-seafloor heights that presumably reflect three age groups, assuming increasing plate depth with age. If the main (1,400 m) group is related to surrounding ~100 million-year-old (e.g., Koppers et al., 2003) seamounts, the oceanic lithosphere was ~70 million years old at the time of seamount eruption, and thus the volcanoes should have been 1 km taller if eroded at sea level at that time. However, the seamounts stand a shorter distance from the seafloor than that, thus they must have eroded (at sea level) at some other point. Unusually thin warm lithosphere and/or later plate tectonic uplift might explain exposure of the summits

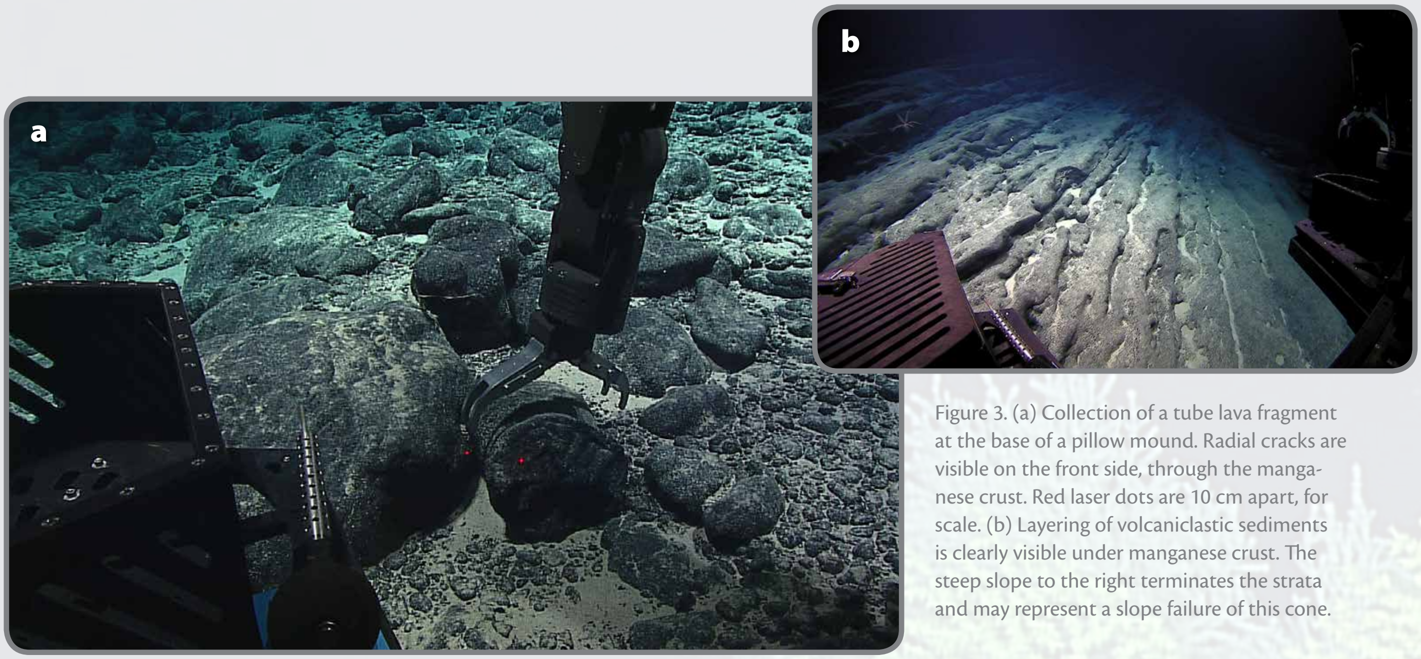



Figure 3. (a) Collection of a tube lava fragment at the base of a pillow mound. Radial cracks are visible on the front side, through the manganese crust. Red laser dots are 10 cm apart, for scale. (b) Layering of volcaniclastic sediments is clearly visible under manganese crust. The steep slope to the right terminates the strata and may represent a slope failure of this cone.

to erosion (Wolfe and McNutt, 1991; Winterer et al., 1993), but more work is needed.

Observations here derive from ROV dives to both ridge crests along the rift zones and guyot summits. The substrate observed during the ridge crest dives is characterized by thick ferromanganese crusts (up to several inches thick) covering pillow and tube lavas (Figure 3). The pillow lavas commonly occur as concentrated mounds separated by more sedimented areas. One guyot summit dive revealed a cone on top of the guyot platform exhibiting clearly layered manganese-encrusted volcaniclastic sediments exposed by small-scale slope failure (Figure 3). The dive to a second guyot covered both the platform and another cone. The platform lacked sediment, and instead was dominated by pillow lavas and a dome-like cone. Therefore, it appears that post-erosional volcanism may occur extensively on guyot summits, possibly covering any existing sediment cap. The occurrence of both volcaniclastic and pillow lava-based post-erosional cones suggests eruptions occurred in up to ~1 km or more water depth, presumably post-dating the drowning of any reef structure. Alternatively, carbonates may have been especially vulnerable to significant Cretaceous climate variation (Föllmi, 2012) so that reef structures were not preserved or formed.

The only location where abundant carbonate deposits were observed was in the shallow water around Wake Island. The carbonate occurred as sand, cobbles, boulders, and large exposures of thinly manganese-coated sequences of mainly shell and coral debris. The carbonate formations were tens of meters tall, with steep outward-dipping strata. Although the contact with the sand was very sharp, the larger carbonate exposures appeared rounded with probable dissolution cavities, likely due to surface weathering during low relative sea level. Subsequent submergence formed the current atoll at the surface.

## Summary of Biological Findings

The primary biological objectives for the ROV surveys during this cruise were to (1) search for high-density coral and sponge communities, (2) document the species composition of these and other communities, (3) search for any commercially valuable species of corals or fishes, and (4) look for and collect specimens of potential new species. High-density communities were indeed discovered during four of the dives, each with its own unique species composition. The most spectacular community was found on a manganese-encrusted ridge that extended out from a guyot south of Wake Island. This site, at 1,400–1,500 m depth, was dominated by huge coral colonies, particularly coralliids (*Hemicorallium* sp.), primnoids (*Calyptrophora* sp.), and isidids mixed in with various other species of corals and sponges (Figure 4a). Another shallower community (500–600 m) was discovered on the east slope of Wake Island. Here, precious gold and bamboo corals (*Kulamanamana haumaea* and *Acanella* sp.) were growing on the edge of a carbonate terrace or fault block (Figure 4b). Thousands of sea pens (*Calibelemnon* sp.) covered the seafloor both above and below this edge. The other two high-density communities were found on adjacent guyots in the northwestern part of the monument. A strange community of an unidentified "two-branch" primnoid in the genus *Narella* mixed with black corals (*Heteropathes* or *Trissopathes* sp.) and an unusual demosponge dubbed the "Kebab" sponge was

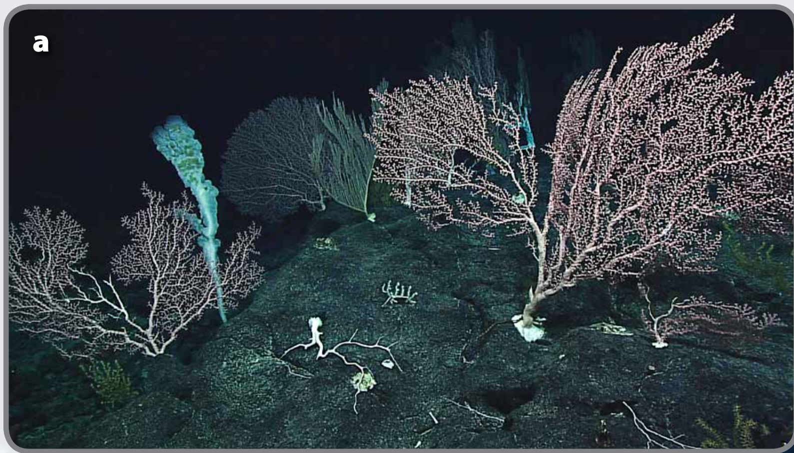




Figure 4. Two examples of different types of high-density communities of deep-sea corals. (a) Deep community dominated by large coralliids (*Hemicorallium* sp.) and primnoids. (b) Shallow community dominated by precious gold coral (*Kulamanamana haumaea*), precious bamboo coral (*Acanella* sp.), and rock pens (*Calibelemnon* sp.).

discovered on one of these guyots. A community of various corals (isidids, coralliids, and primnoids) mixed with large pheronematid glass sponges was discovered on the other. The densest groupings of corals and sponges were observed on the topographic highs, and each of these communities included a high diversity of less abundant species. The other dive sites in the monument were found to have moderate- to low-density communities, each differing in composition and dominant species.

The fish communities found inside the Wake unit were composed of both familiar and unusual species. Familiar fish encountered during dives deeper than 800 m were cutthroat eels (Synaphobranchidae), cuskeels (Ophidiidae), rattails (Macrouridae), and halosaurids. Alfonsinos (*Beryx* sp.) and tinsel fish (*Grammacolepus brachiusculus*) dominated during a shallower dive—Alfonsinos are a commercially valuable species elsewhere in the Pacific, and the tinsel fish were observed in far greater numbers here than have been seen elsewhere. Unusual fishes observed included a sorceress eel (*Venifica* sp.) and a species of macrourid suspected to be very rare (Figure 5).

Forty-one biological specimens were collected during Deepwater Wonders of Wake: Exploring the Pacific Remote Islands Marine National Monument. However, at present, the number of new species among these is difficult to estimate since taxonomic specialists have not had a chance to examine them. Because this cruise was the first deepwater biological investigation around Wake, all of the animals collected, as well as imaged by the ROV cameras, are new records for this area.

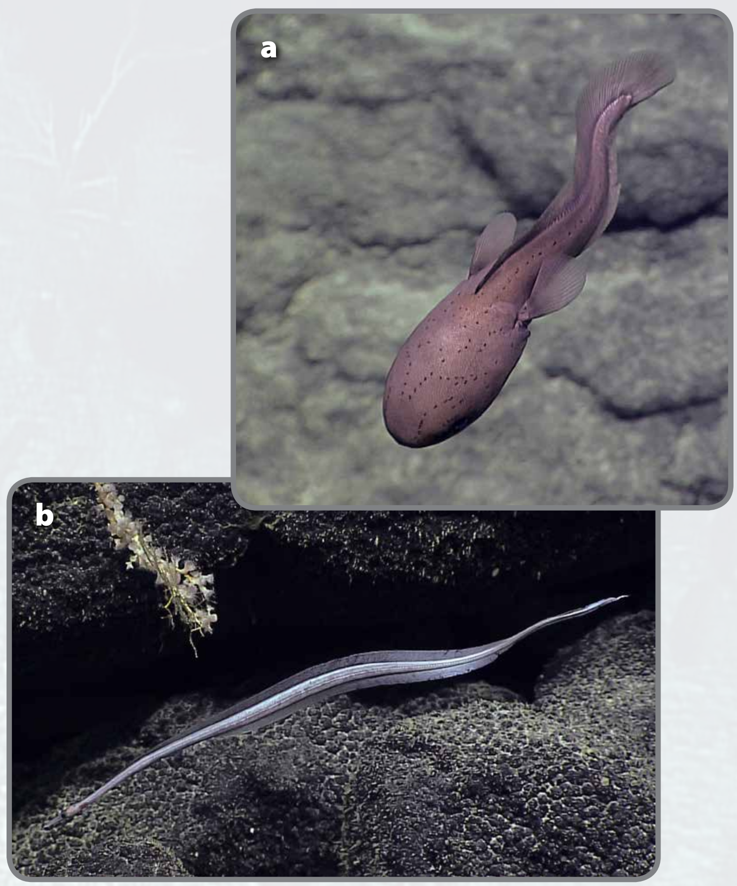



Figure 5. Two examples of unusual fishes observed during the dives. (a) A suspected rare and unusual species of rattail (Macrouridae). (b) Rare sorceress eel (*Venifica* sp.).

# Exploring the Underwater Archaeology of World War II

By Frank Cantelas, Hans Van Tilburg, Gary Fabian, Christopher Kelley, Jeremy R. Kinney, and Anthony Tully

Between 1941 and 1945, American and Japanese forces confronted each other across many remote Pacific locations. Physical remains of World War II, found on islands, on atolls, and underwater, now comprise an extensive archaeological record. The CAPSTONE effort provided the opportunity to visit two underwater locations that hold a significant place in American history, marking the beginning and the end of the war. The Battle of Wake Island became one of the familiar wartime catchphrases that rallied Americans to a national war effort, while the airbase on Tinian Island served to launch air attacks against Japan that ultimately ended the war.

On December 8, 1941, only a few hours after the attack on Pearl Harbor, on the opposite side of the International Date Line, Japanese aircraft bombed American installations being constructed on Wake Island. Early in the battle, US Marines manning a shore battery sank the Imperial Japanese Navy destroyer *Hayate*, making it the first large surface vessel sunk by the United States in the Pacific War. Despite a spirited defense, Japanese invasion forces took the island on December 23.

Today, Wake Atoll is a National Historic Landmark, yet deepwater sites associated with the battle have never been explored. Using numerous eyewitness accounts of the sinking, *Hayate* became the focus for NOAA Ship *Okeanos Explorer* mapping efforts along the south shore. Analysis of multibeam sonar data revealed several possible targets near the reported sinking that became the subjects for an ROV dive.

The science team hoped to confirm the location of *Hayate*, complete a perimeter survey of major features, and assess the status of deterioration. Upon close observation, the team quickly realized it was not *Hayate* but instead another vessel of similar size. Through real-time online collaboration, the ship was identified as *Amakasu Maru No. 1*, a Japanese water tanker sunk by *Tambor*-class submarine USS *Triton* (SS-201) on December 24, 1942, a year after the attack on Pearl Harbor, with the loss of 12 crew members (Figures 1 and 2).

The vessel sits upright on sand and large rocks with a slight list to starboard. The topside superstructure shows damage from sinking and ensuing deterioration caused by the underwater environment. The masts have fallen, the smoke stack has toppled and flattened, cabin spaces are deteriorating, and the wooden deck is eroded or missing. The cargo hold contains large steel rectangular containers, possibly water tanks. Two deck guns had been fitted fore and aft with loaded ammunition boxes (Figure 3). Several rounds from the stern 8cm/40 naval gun appear to be missing.

Instead of providing details on the historic Battle for Wake Island, the discovery of *Amakasu Maru No. 1* opens a window on Japanese merchant vessels and the naval supply train during the years following Wake's occupation. Auxiliary ships,

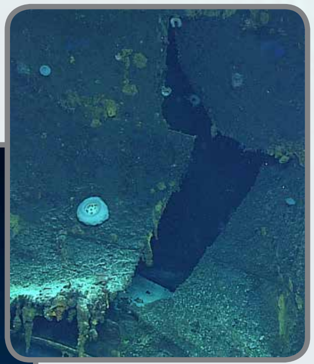


Figure 2. USS *Triton*'s patrol report makes clear that her torpedoes struck the port side of *Amakasu Maru*, and the ship sank stern first. One of two large breaks shown here on the lower starboard hull suggests explosion damage carried through the hull from the port side, or the holes were caused when the hull struck large rocks on the bottom.

Figure 1. Exploration often leads to the unexpected. On close examination, it quickly became apparent that the bow of this shipwreck did not match the characteristics of the Imperial Japanese Navy destroyer *Hayate*, the expedition members anticipated finding. *Amakasu Maru* shown here is an example of the unsung auxiliary merchant ships methodically pursued and destroyed by both sides during the war.

Figure 3. For defensive purposes, *Amakasu Maru* mounted an 8 cm naval gun on the bow and stern. The gun mounted on the bow has collapsed against the ammunition boxes that are now lined up along the top of the barrel.

usually overshadowed by combat vessels and actions, provided the backbone of logistical support for all naval forces. *Amakasu Maru* was the flagship for some 40 similar merchant vessels built before the war (Division of Naval Intelligence, 1945). During WWII, US submarines sank more than five and one-half times the numbers of merchant ships, 1,113 vessels or 4,779,902 tons, compared to 201 naval vessels, or 540,192 tons (Joint Army-Navy Assessment Committee, 1947).

The second CAPSTONE site lies to the west. Tinian Island in the Northern Marianas, 1,500 miles (2,400 km) south of Tokyo, was captured by the United States in August 1944, and it became one of the largest airbases in the world (a year later, it would be the launch point for the atomic bomb attacks against Hiroshima and Nagasaki). In November 1944, the Twentieth Air Force initiated strategic bombing of Japan from Tinian using the B-29 Superfortress. The aircraft featured many advanced technologies, including pressurized cabin space, that made it capable of long-range missions—including 3,000-mile (4,800 km) round trips to Japan. With a wingspan measuring just over 141 ft (43 m), the B-29 was one of the largest aircraft flown by the United States in World War II. Between late 1944 and the end of 1945, several B-29s flying from Tinian's North Field, and from fields on Saipan, suffered mechanical difficulties or other problems and crashed in the channel (J. Meyer, USAF, *per. comm.*, May 16, 2016).

The deep floor of Saipan Channel, where many of the crashes reportedly occurred, is characterized by strong tidal currents and a relatively flat and sandy bottom ranging in depth from 350 m to 400 m. Several nondescript sonar anomalies found in this area correspond to the expected signature of fragmented aircraft wreckage. Missing Air Crew Reports for aircraft lost in this area describe how most of the planes broke apart or even exploded (Missing Air Crew Reports, 1942–1947).

One relatively high backscatter anomaly became a subject for closer investigation. As ROV *Deep Discoverer* reached the seafloor, a ghostly reminder of World War II quickly came into view when the wing and engines of a B-29 Superfortress were revealed (Figure 4). The wing assembly is upside down, with landing gear retracted. Three of the four radial engines are still mounted. Debris aft of the wing, likely associated with the fuselage, contains a parachute, an oxygen cylinder, and the fourth engine. Following the debris trail northeast led to the discovery of the forward gun turret and part of the flight engineer's station (Figure 5). On the B-29, both features were located forward of the wing. The search for debris ended with the discovery of the tail's horizontal stabilizer (Figure 6).

The most likely causes for the aircraft to break apart are an explosion during flight, a crash, or ditching on the water. Although the identity of the B-29 remains unknown, it is one of several aircraft lost in this part of the channel.

The Pacific Campaign of WWII spanned the ocean from the Aleutians to Australia, and traces of the major battles, as well as the more mundane activities of keeping military forces fed and watered, lie in deep water. These dives provided an opportunity to contribute information related to the cultural heritage of WWII in the Pacific.

Figure 4. ROV *Deep Discover* hovers over the wing of a B-29 Superfortress resting on the sandy bottom of Saipan Channel. Two of the three intact engines are visible as is the remains of the fourth detached engine in the debris field to the right.

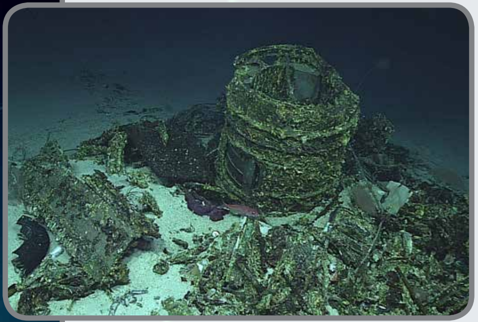


Figure 5. The cylindrical forward gun turret came to rest upside down, with the gun barrels embedded in the seafloor. Technology advancements in the B-29 allowed the gunner to operate this turret remotely from the pressurized crew compartment.

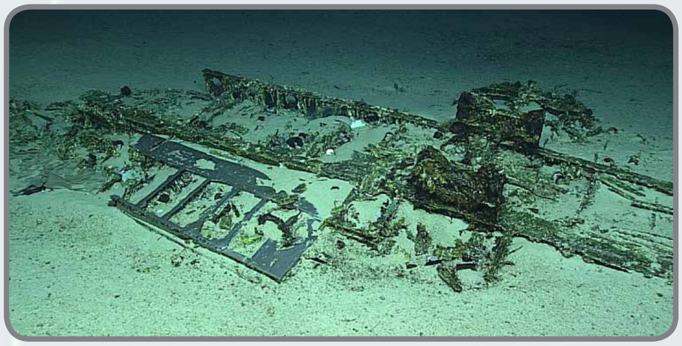


Figure 6. The horizontal stabilizer on the B-29's tail marked the furthest extent of the crash site investigated by NOAA Ship *Okeanos Explorer*.

# Hidden Ocean: Exploring the Dynamic Chukchi Borderlands

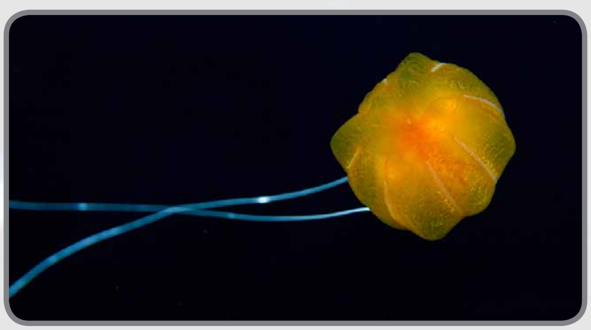
By Eric Collins, Russell Hopcroft, Katrin Iken, and Amy Bowman

From July to August 2016, scientists from the University of Alaska Fairbanks led a 40-day NOAA OER-funded expedition to explore one of the most remote locations on Earth, the Chukchi Borderlands. Aboard US Coast Guard Cutter *Healy* with Oceaneering's ROV *Global Explorer*, the expedition united an international and interdisciplinary team of scientists, media personnel, and educators. The goal of the mission was to create a greater understanding of this rapidly changing region. Work from this mission improved baseline observations of the marine environment while helping to expand understanding of the Arctic's marine biodiversity, as well as climate and ecosystem structure and function.

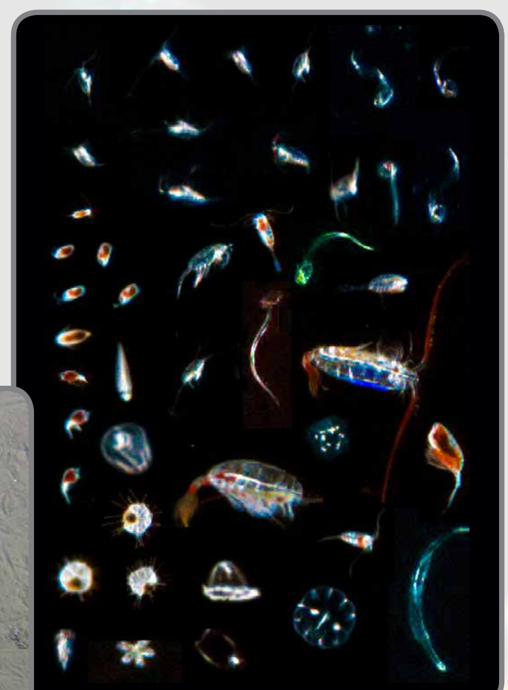
The mission built upon the work of prior expeditions and data, including the rich US Extended Continental Shelf Project Arctic data set, by augmenting the available geological, hydrographic, and bathymetric information with detailed biological observations. Science teams assessed the diversity of life within the Arctic's three major realms—sea ice, water column, and seafloor. They employed an ecosystem approach to investigating microbial communities, planktonic organisms, and benthic fish and invertebrate communities. In all, this expedition visited 13 stations covering poorly known areas in a locale that is profoundly changing due to warming temperatures and sea ice loss.

The teams used a variety of tools to explore the Chukchi Borderlands, including traditional ice cores, nets, grabs, and trawls to collect sea ice, pelagic organisms, benthic organisms, and fish, respectively. They also surveyed seabirds and marine mammals throughout the cruise using standardized observation methods. Ultra-high-resolution cameras outfitted on ROV *Global Explorer* were used to observe organisms and their behaviors in their natural habitats. The ROV also has capacity to collect some of the organisms observed. Scientists are using classical methods based on body characteristics and genetic analyses to identify and describe species. Mapping data collected in the Arctic for the US Extended Continental Shelf Project were instrumental in selecting the habitat targets for this expedition.

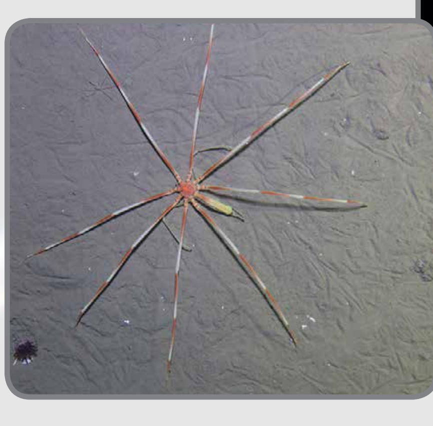
This expedition found the Chukchi Borderlands to contain enhanced quantities of marine life compared with the nearby deeper abyssal plains. Regions of pockmarks that indicate former sites of gas hydrate venting appeared to have unique seafloor faunal assemblages. In addition, five undescribed comb jellies were observed and collected, some exploiting unique habitats, during 18 ROV dives to a maximum of 2,200 m depth. The high resolution of the camera greatly increased the scientists' abilities to identify animals in situ. As they continue to process the hundreds of preserved samples, more new species are being discovered, and observations of species previously unreported for the area are being noted. The science teams collected approximately 200 terabytes of ultra-high-definition video from the ROV, plus underway



(above) This image of "Mr. Pumpkin" in the water column was taken by ROV *Global Explorer*. It is important to image any undescribed species in its own habitat. *Photo credit: Oceaneering-DSSI*



(right) This mosaic shows a variety of organisms imaged by the Visual Plankton Recorder during this expedition. All images are to the same scale. *Image credit: Dhugal Lindsay, JAMSTEC*



(right) The pycnogonid, commonly known as a sea spider, is a deep-dwelling species aptly named *Colossendeis proboscidea* for its large size (~20 cm or 8 in across) and the long proboscis that the species uses to bore into its prey. *Photo credit: Oceaneering-DSSI* oceanographic and meteorological data, multibeam bathymetric data, and temperature-salinity-nutrient profiles of the water column. They also retrieved and redeployed an oceanographic mooring on the Chukchi shelf that measured a suite of physical, chemical, and biological parameters for the past year. It is through instruments such as these that we learn about the broader seasonal patterns in the waters of the Chukchi region, how they vary from year to year, and whether longer-term cycles or trends occur. All data and samples will be made publicly available through national archives.

Unlike many scientific expeditions, this one included a significant contingent of media professionals from three major sources plus a NOAA Teacher at Sea. The web coordinator from the Global Foundation for Ocean Exploration focused on daily logs, video, and still imagery. The media group chronicled adventures aboard *Healy* with the intent of publishing a magazine feature article and producing an Arctic expedition documentary. This group also obtained footage of the small and microscopic creatures that inhabit the ocean to build another documentary. Preliminary expedition media, education, and outreach content suggests that new public or classroom materials could continue to be released over the next two years.

There is still much to learn about the Chukchi Sea region and its habitats. By building upon this and previous work, and enhancing our national and international partnerships, NOAA will continue to strengthen foundational science. This will help scientists understand and detect Arctic climate and ecosystem changes while improving stewardship and management of our precious ocean resources in the Arctic.

(left) The snailfish is a common benthic fish species found in the Chukchi Borderlands. This fish was sampled by ROV *Global Explorer* during a benthic dive. *Photo credit: Microcosm Film*

(right) Eric Collins handles the corer with Kyle Dilliplaine and Brian Ulaski. The collected ice cores can be seen in the plastic tubing at the bottom of the frame. *Photo credit: Caitlin Bailey, GFOE*

(above) A ribbon seal rests on an ice floe. *Photo credit: Caitlin Bailey, GFOE*

## GLACIER BAY

By Rhian Waller, Kasey Cantwell, and Amy Bowman

From March 17 to March 30, 2016, a University of Maine-led team of scientists from the US Geological Survey, the National Park Service, University of Alaska Fairbanks, and NOAA conducted the first-ever deepwater exploration of Glacier Bay National Park and Preserve, one of the few places in the world where deep-sea corals exist in shallow waters. Using diver-based and ROV surveys, scientists found abundant cold-water corals and associated organisms throughout the fjords—the first documentation of cold-water coral ecosystems existing within our national parks. This expedition also marked the first observation of stony corals within the park, as well as the greatest global depth observation for one species of stoloniferous octocoral, a type of encrusting coral. The mission helps address NOAA's need to better characterize unknown areas of our ocean basins, as well as the agency's responsibility to understand essential fish habitats, climate variability, and deep-sea coral life history and population structure.

(below) A large colony of red tree coral is brought aboard R/V *Norseman II* by Jim Wells (left) and Eric Glidden. This colony was collected to better understand how these corals interact with their environments and how the populations have developed in the bay. *Photo credit: Dann Blackwood, USGS*

(left) At times, it was difficult to see the red tree corals beyond the large schools of fish that were documented at several sites. *Photo credit: UCONN/NURTEC*

# Engagement 2016: A Commitment Reaching Far and Wide

By Paula Keener, Emily Crum, Katie Wagner, and Catalina Martinez

During the 2016 expeditions, the Ocean Explorer website (http://oceanexplorer.noaa.gov) was the focal point for OER communications from NOAA Ship *Okeanos Explorer*. The site received more than 12 million visits, breaking all previous records. Web content, including logs, daily updates, images, and videos, brought expeditions to life as they happened, while background content and educational materials enriched the context of the missions. Armchair explorers were once again invited to join in *Okeanos Explorer* activities as ROV *Deep Discoverer* streamed real-time video from the ship to anyone with an Internet connection. Live video feeds received a record-breaking 4.3 million views, a 180% increase over 2015 viewership. The launch of a mobile application enhanced live video viewership by allowing users to follow ROV *Deep Discoverer* into the sea in real time on iOS or Android devices; the application was downloaded more than 6,800 times.

Throughout the year, OER continued to use social media to engage and inform the public. OER's Facebook account surpassed 100,000 likes, Twitter followers increased to over 80,000, and the YouTube channel had more than 34,000 subscribers. Instagram was a positive new addition to the suite of social media tools. Two-way communications with the public via social media included a Reddit "Ask Us Anything" session focusing on *Okeanos Explorer*'s mapping capabilities and a TweetChat with scientists during an expedition in the Marianas Trench Marine National Monument. To celebrate World Oceans Day in June, OER joined exploration partners Schmidt Ocean Institute and Ocean Exploration Trust for a Google+ Hangout On Air. The live event featured scientists on board *Okeanos Explorer*, E/V *Nautilus*, and R/V *Falkor* as they shared how they explore the ocean using advanced underwater technologies with a worldwide audience.

CAPSTONE continued to offer on-site professional development opportunities to educators in remote locations to enhance ocean literacy. OER worked closely with NOAA Fisheries' Marine National Monument Program, the National Marine Sanctuary of American Samoa, the Commonwealth of the Northern Mariana Islands Public School System, and the American Samoa Department of Education to design an eight-hour professional development course titled: *Why Do We Explore the Deepwater Areas of American Samoa?* The course was offered to 50 educators at the Tauese P.F. Sunia Ocean Center, which welcomes visitors to the National Marine Sanctuary of American Samoa. Using the NOAA Ship *Okeanos Explorer* Education Materials Collection (http://oceanexplorer.noaa.gov/okeanos/edu/welcome.html), educators learned about submarine features and ocean ecosystems within their own deepwater "backyards" through

(below) An educator blows into a solution during an Exploring the Deep Ocean professional development activity featured at the Tauese P.F. Sunia Ocean Center, a visitor center for the National Marine Sanctuary of American Samoa in Pago Pago.

(left) Explorer-in-Training Calder Atta is shown next to *Okeanos Explorer's* ROV *Deep Discoverer*. *Photo credit: Caitlin Ruby*

(right) Explorers-in-Training on board NOAA Ship *Okeanos Explorer*, with Expedition Coordinator Derek Sowers (left), are Caitlin Ruby, Calder Atta, Briana Grenier, Melissa Price, and Stephanie Martinez-Rivera. Watch Lead Daniel Freitas is in back.

professional learning opportunities tied to CAPSTONE expeditions. Topics included climate change, ocean acidification, submarine volcanoes, seamounts, hydrothermal vents, and advanced technologies for ocean exploration. Nearly all participants indicated they would use workshop content in their classrooms, potentially reaching more than 1,400 students and helping to build the capacity of a future STEM workforce. The workshop also introduced educators to 2017 *Okeanos Explorer* CAPSTONE expeditions in their region.

Opportunities were numerous during 2016 for OER and partners to communicate the importance of ocean exploration to more than 1,000 people from local communities on Guam and Saipan through presentations, workshops, and ship tours. Expedition briefings were provided to the Commonwealth of the Northern Mariana Islands Senate in Saipan and presented at a "Science Sunday" talk hosted by the National Park Service in Guam. A new Exploration Command Center (ECC) at UnderwaterWorld Guam enabled scientists and the public to participate in ROV dives in real time, and over one hundred high school students on Saipan participated remotely through telepresence technology. Interactions with *Okeanos Explorer* were also featured at the Exploratorium's *Science on a Square* in San Francisco with visitors and on the museum's website.

Through partnerships among OER, OET, the NOAA Educational Partnership Program, the University Corporation for Atmospheric Research, and the University of New Hampshire, students had opportunities to participate in the NOAA OER Explorer-in-Training (EiT) Program and the OET Science & Engineering Internship Program. The EiT internships provided students with at-sea experiences on board *Okeanos Explorer* that included skill development in support of building STEM capacity in NOAA mission sciences. Participants included undergraduates and graduate students, early career scientists, and students from underrepresented groups. A total of 17 Explorers-in-Training participated in CAPSTONE expeditions this year, including two who were engaged via telepresence in a mapping cruise at the UNH ECC as a demonstration project to teach multibeam mapping from an ECC setting, a first for the OER EiT Program. For more information on OET internships, see page 21.

Media continued to play a critical role in OER's efforts in public engagement. Press releases and "Exploration Alert" emails kept media representatives, social media managers, and public affairs contacts informed of expedition activities and discoveries and resulted in hundreds of articles on several never-before-seen animals, driving audiences to live video online. These media outreach efforts resulted in dozens of interview requests and significant media coverage of *Okeanos Explorer* expeditions. Stories were generated by hundreds of outlets ranging from NBC, CNN, Associated Press, *Scientific American*, *TIME*, and The Weather Channel, to Gizmodo, BuzzFeed, and HowStuffWorks.

(below) A VIP tour of NOAA Ship *Okeanos Explorer* docked at Naval Base Guam was led by First Mate Kevin Lackey and Expedition Coordinator Kasey Cantwell.

(above) Principal Investigators Shirley Pomponi and Patricia Fryer are interviewed by Isa Baza of Guam's KUAM News in *Okeanos Explorer*'s control room prior to departure of a 2016 Deepwater Exploration of the Marianas expedition.

During 2016, OER continued to encourage the next generation of ocean explorers, scientists, and engineers through the numerous outlets described above. The collective engagement efforts also supported the NOAA-wide directive to address equity in access to NOAA outreach and education resources by reaching out to underserved and underrepresented groups. In working in the central Pacific, we reach even further into remote locations where access to resources is limited. By including a focused, on-site, targeted professional development effort for educators, OER sought to enhance the STEM capacity of a remote region by bringing ocean exploration knowledge, awareness, and skill-based resources to small, remote Pacific Island communities and by providing tools that they might use to build their future workforces. Enhancing traditional and scientific knowledge and understanding the surrounding marine environment is critical to conserving and managing the region's remarkable habitats and ecosystems. The results assist with ocean resource management in helping tribal leaders, citizens, businesses, and governments make informed decisions that will ultimately protect lives, property, and economic well-being.

# A Glance at Schmidt Ocean Institute

## An Introduction By Wendy Schmidt

The future of humanity depends on how quickly and deeply we can understand our ocean and work to protect it.

Our planet has been changing in unprecedented ways in the Anthropocene. The ocean, which absorbs most of the $CO_2$ emitted from the burning of fossil fuels, has already become 30% more acidic since the Industrial Revolution. If this happened to your body chemistry, you'd be in the emergency room. We have a planetary emergency in progress.

Over the past 50 years, the world ocean has suffered mightily from overfishing as well as from numerous forms of pollution: for example, physical pollution in the form of discarded plastics, chemical pollution from oil spills and sewage containing endocrine disruptors, and noise pollution from deep-sea drilling and mining operations. The result is long-term disruption of ecosystems that evolved over millions of years and that contain life forms and natural resources that we have not even begun to explore, yet understand. It is hard to imagine how we could attack our ocean planet more purposefully than we are doing right now.

Our mission at Schmidt Ocean Institute (SOI) is to help expand public understanding of why ocean health matters to all of us, no matter where we live. We all depend on the ocean—for the air we breathe and the food we eat, and for the hydrologic system that produces the comparatively small, but necessary amount of fresh water that fills our streams, rivers, and aquifers. The rigorous research expeditions aboard R/V *Falkor* inspire a culture where data collected and discoveries made at sea are shared transparently in real time both within the scientific community and with the greater public.

It is time to rapidly expand the frontiers of our knowledge about the ocean that covers 71% of Earth's surface. Since March 2012, when we launched *Falkor*, our crew and captains have traveled around the world more than five times, and have mapped an area larger than 82 times the size of the Grand Canyon.

The scientists invited to come aboard *Falkor* through a peer-reviewed process have access to our advanced lab spaces and visualization tools, onboard high-performance computing system, ship-to-shore communications, and a fleet of remotely operated vehicles with high-resolution cameras. In 2016 alone, we conducted 156 ROV dives and streamed more than 635 hours of live footage on YouTube from some of the deepest parts of the ocean. Over the past five years, we have discovered new species in unexpected places, named undiscovered seamounts, and even located a famous Antarctic exploration vessel lost in the North Atlantic since World War II.

The scientists who have participated in research on board *Falkor* represent 138 institutions in 27 countries, and now form a community whose discoveries are changing the way the science is practiced. They inspire our global audience with new questions, mysteries, and a search for the unknown, but also with human stories. The ocean contains 99% of the living space on the planet and 50%–80% of all life forms—and these are mostly unexplored by humans.

The time is now to think about how we participate in this natural world beneath the sea and are deeply connected to it. Every expedition yields new knowledge that brings us closer to achieving this goal.

# R/V *Falkor* 2016 Field Season

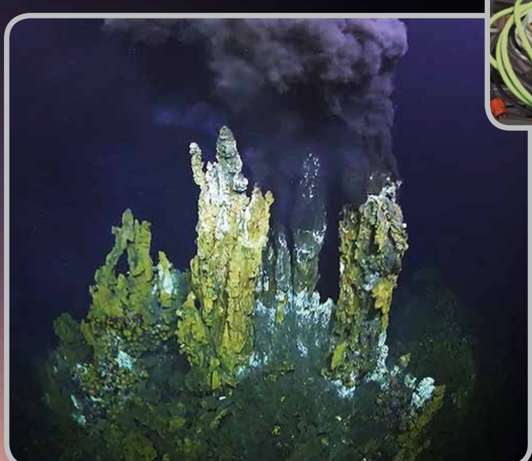
*Falkor* Bosun Michael Utley and scientist Tristen Horner deploy a McLane Pump off the aft deck to collect seawater in low oxygen zones of the ocean. *Photo credit: SOI/Monika Naranjo Gonazles*

## Investigating Life Without Oxygen in the Tropical Pacific

– Chief Scientist: Mak Saito, Woods Hole Oceanographic Institution

A new protein biomarker technology was used for the first time to study oxygen minimum zones across 7,000 km of ocean. Developed by Mak Saito and colleagues, targeted metaproteomics employs proteins to detect marine microbial populations and analyze their interactions with ocean chemistry. The results will improve understanding of critical chemical interactions within oxygen minimum zones and help to identify long-term changes in these regions. Because the expedition occurred during a strong El Niño year, the samples will permit studies of how warmer seawater conditions influence key microbial processes. Comparisons of these data with those from more typical years could provide valuable insight into ecosystem responses to El Niño.

Principal Investigator Tom Kwasnitschka works on the setup of four cameras and a laser line on ROV *ROPOS* during the "Virtual Vents" research cruise. *Photo credit: SOI/Björn Kurtenbach*



ROV *ROPOS* image showing chimney structures and fluid release at a black smoker hydrothermal vent. *Photo credit: SOI/ROPOS*

## Virtual Vents: The Changing Face of Hydrothermalism

– Chief Scientist: Tom Kwasnitschka, GEOMAR Helmholtz Centre for Ocean Research Kiel

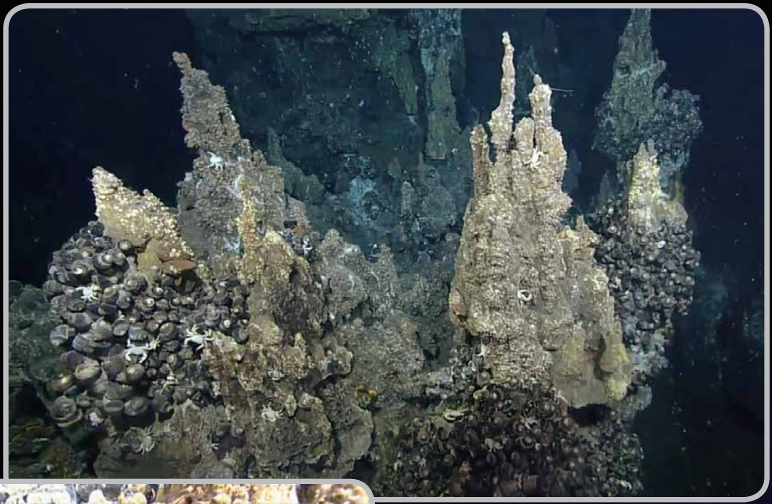
Using innovative imaging equipment, the science team mapped an entire hydrothermal vent field in the northern Lau Basin, capturing 4K video sequences for immersive hemispherical display in real time. The cruise resulted in the production of a series of 1 cm resolution, three-dimensional models of the vent groups that revealed fine-scale geological and biological details. Projection of this footage using virtual reality technology offers a new way for scientists to access these remote sites and also creates an immersive tool for public engagement. All of the ROV dives are publicly available on SOI's YouTube page (https://www.youtube.com/user/SchmidtOceanVideos).

(background) R/V *Falkor* at sunset over the Timor Sea. *Photo credit: SOI/Logan Mock Bunting*

## Ecosystem Dynamics of Hydrothermal Vent Communities

– Chief Scientists: Peter Girguis, Harvard University, and Charles Fisher, Pennsylvania State University

Returning to the Lau Basin with a new science team, ROV *ROPOS* collected hydrothermal vent observations to create high-resolution two- and three-dimensional photomosaics that contribute to a 10-year time series. This research provided new knowledge about the area's volcanic activity and the ecology of its hydrothermal vent species, making critical baseline data available from an area with potential for deep-sea mining. Based on initial comparisons of the imagery, the long-term study sites are more stable than previously thought. This observation challenges previous understanding that vent environments are highly dynamic, resulting in concern about potential environmental impacts from deep-sea industrial mining.



These mussels and crabs captured by ROV *ROPOS*'s cameras are examples of the amazing life forms that flourish on and around deep-sea hydrothermal vents. *Photo credit: SOI/ROPOS*

## Study of the Sea-Surface Microlayer and the Air-Sea Boundary

– Chief Scientists: Oliver Wurl, University of Oldenburg, Christopher Zappa, Lamont-Doherty Earth Observatory (LDEO), and William Landing, Florida State University

A science team deployed a variety of instruments to scan the sea surface with cameras and highly sensitive thermal and optical measuring instruments for studies of the surface microlayer's vital role in the uptake and release of greenhouse gases. The tools used included an unmanned aerial vehicle (UAV) that had never been used for research purposes on a ship. Other autonomous tools were deployed during the cruise to explore trace metals, greenhouse gas exchange, wind and wave effects on air-sea transfer, and microbial communities. The science team aims to improve computer models for forecasting climate change with the newly collected data from this cruise. Successful use of the UAV on this cruise led to a grant from The Moore Charitable Foundation to LDEO for studies of Arctic sea ice change.

(top) Joe McDaniel integrates scientific instruments into the UAVs. The data collected will provide information about processes affecting air-sea exchange. (bottom) UAVs carrying scientific instruments took off from a ship (*Falkor*) for the first time, without the help of any catapult or launching system. It was also the first time the HQ-60B model completed a science mission. *Photo credit: SOI/Monika Naranjo Gonazles*

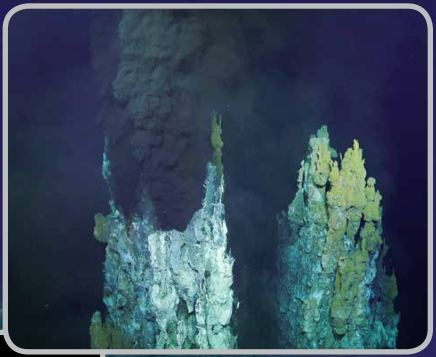
## A Changing River: Measuring Nutrient Fluxes to the South China Sea

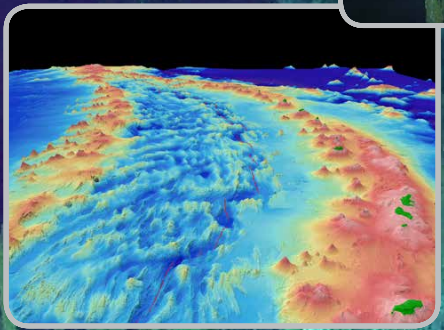
– Chief Scientist: Joseph Montoya, Georgia Tech

During *Falkor*'s first visit to Vietnam, a science team investigated the Mekong River's influence on the South China Sea. The Mekong has been modified extensively by, for example, sewage loading, fertilizer use, mangrove destruction, and dam construction. The science team surveyed over 21,000 km$^2$ of ocean and collected numerous water samples. Data resulting from analysis of these samples will be used to model terrestrial-oceanic linkages for studies of the impacts of land-use change on marine ecosystems.

Chief Scientist Joseph Montoya supervises deployment of a spectroradiometer, one of the instruments used by the interdisciplinary science team to collect data for numerical models. *Photo credit: SOI/Monika Naranjo Gonazles*

(right) An active black smoker chimney, part of the "Two Towers" formation. *Photo credit: SOI*
(below) Computer-generated view of the seafloor in the Mariana back-arc. The Mariana Trench is in the lower right (in purple) and the island of Guam is in the middle right (in green). *Image credit: SOI/Susan G. Merle*

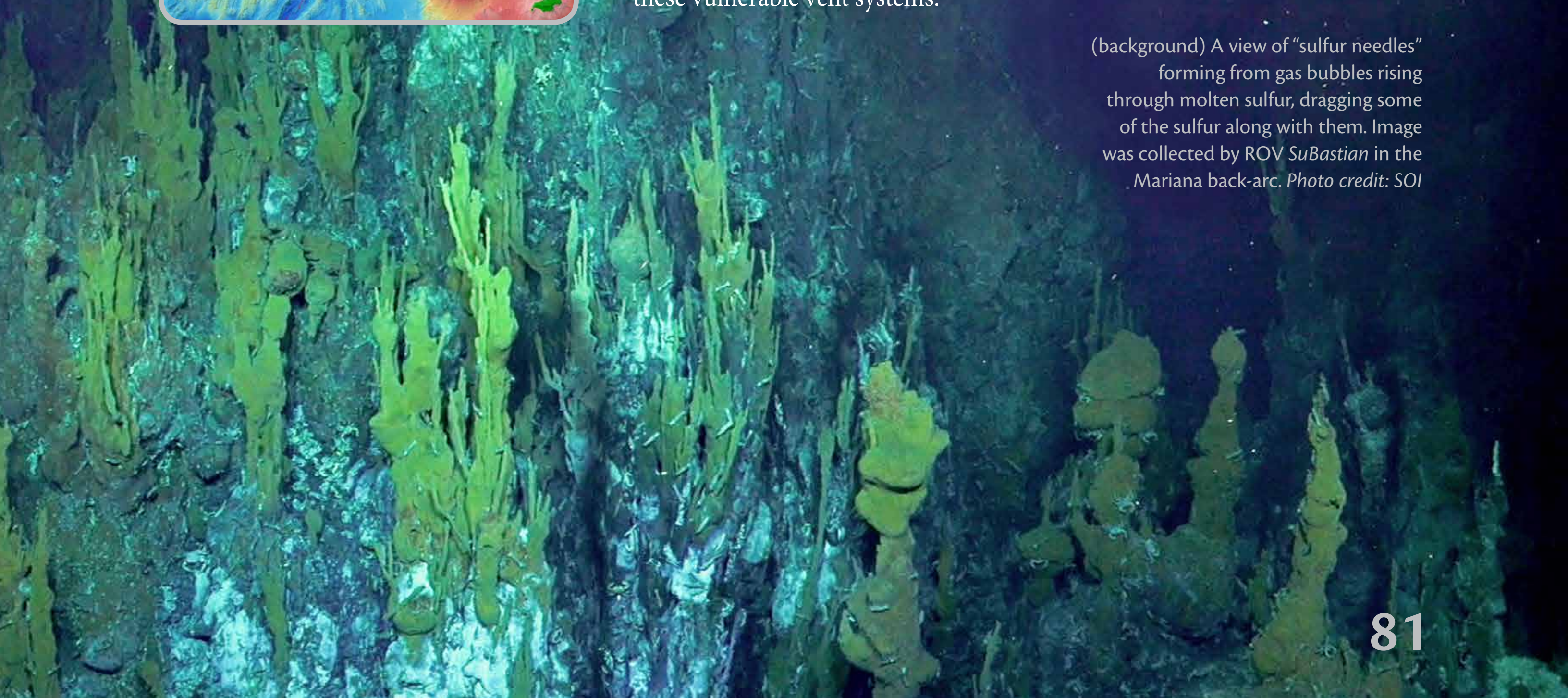




## Searching for Life in the Mariana Back-Arc

– Chief Scientist: David Butterfield, JISAO, University of Washington

The first scientific deployment of SOI's new 4,500 m ROV *SuBastian* was completed on the last cruise of 2016. *SuBastian* supported the study of the relationships between chemistry, geology, and biology at hydrothermal vent sites along the Mariana back-arc with collection of more than 250 hours of live-streamed deep-sea HD video. Venting at these sites was found to be relatively long-lived, lasting in some cases for decades. The multidisciplinary science team confirmed that the back-arc ecosystems are distinct from the nearby volcanic arc hydrothermal systems. Their observations support the idea that geological and chemical settings play an important role in defining the composition of animal communities inhabiting hydrothermal vents, and will help scientists better understand these vulnerable vent systems.



(background) A view of "sulfur needles" forming from gas bubbles rising through molten sulfur, dragging some of the sulfur along with them. Image was collected by ROV *SuBastian* in the Mariana back-arc. *Photo credit: SOI*

# Global Networks

## Sharing Science and Partnership Projects

In its first four years of active participation in the global science community, SOI hosted at sea more than 465 scientists representing some 138 institutions in 27 countries. The Institute seeks to inspire and reach out to both scientists and the public by live streaming ROV dive video while connecting classrooms and the public to the ship, addressing public questions, and providing berths of opportunity for students and artists. We conducted our first tri-ship Google Hangouts On Air in June 2016 with NOAA Ship *Okeanos Explorer* and E/V *Nautilus* to celebrate World Ocean Day. SOI makes its entire dive series available online, offering a collection of video that enables anyone to follow deep-sea research.

The first tri-ship Google Hangouts on Air on World Ocean Day (06.08.16), connecting live E/V *Nautilus*, NOAA Ship *Okeanos Explorer*, and R/V *Falkor*. *Photo credit: SOI*

ROV *ROPOS* view of chimney structures and fluid release at a black smoker hydrothermal vent inhabited by a cluster of vent snails. *Photo credit: SOI/ROPOS*

### Video Data and Tagging

In conjunction with LDEO, SOI provided support for a summer 2016 workshop to discuss video imaging and data needs. Additional support was provided to test a video annotation program called Ocean Video Lab, which allows users to explore and annotate any publicly accessible underwater video posted on YouTube. Future plans include deployment of a search interface that will hunt across all annotations, and integration of openly accessible related data from various repositories. SOI also provided assistance for development of software that enables scientific annotation of imagery using standards defined or selected by users. This tool was demonstrated to research collaborators who will sail on *Falkor* in 2017, and two teams planning work with ROV *SuBastian* during that season have expressed interest in using the system.

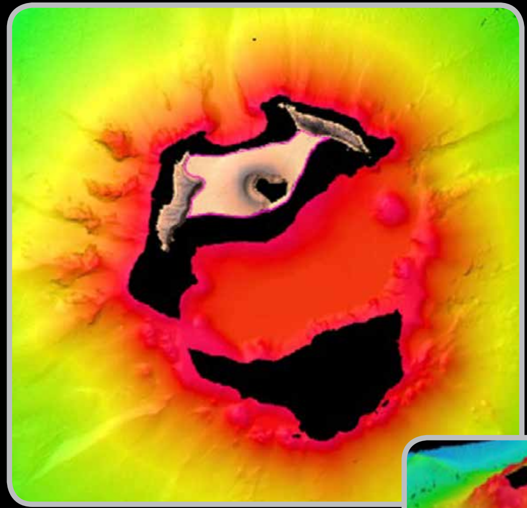
### Technology Sharing

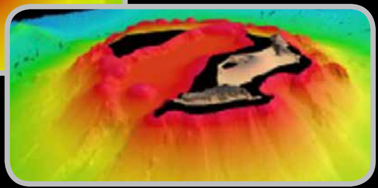
*Falkor* is the only research vessel with a high-performance computing system, allowing scientists to analyze large data sets as soon as they are collected. This capability can be used to make decisions about data collection strategies during surveys. During the 2016 field season, a group of scientists used its capabilities to process extremely high-resolution images from ROV *ROPOS* cameras. These images are being incorporated into a full-color, textured, three-dimensional model of hydrothermal vents using virtual reality tools. The high-performance computing system was also instrumental in processing large amounts of data collected from the air-sea boundary for a holistic study of the sea surface.

(background) ROV *SuBastian's* first night dive in waters off of Guam. *Photo credit: SOI*

## Mapping Remote Areas

While in Tonga, *Falkor* conducted the first high-resolution undersea mapping of one of the newest islands on Earth—unofficially named Hunga Tonga Hunga Ha'apai (HTHH). The data collected will contribute to a project with NASA and LDEO to create a three-dimensional characterization of the new island. Significant joint mapping efforts between *Falkor* and *Okeanos Explorer* that were also made south of Guam (Santa Rosa Reef) included discovery of several new seamounts. A publicly available poster details this work, and was shared with policymakers and the community.





The first high-resolution undersea maps of one of the newest islands on Earth—unofficially named Hunga Tonga Hunga Ha'apai. *Image credit: SOI/Colleen Peters and Vicki Ferrini*


*Falkor* Bosun Michael Utley helps to place ROV *SuBastian* onto the aft deck during its first sea trial deployment in Guam. *Photo credit: SOI/Yuko Inatsuki*

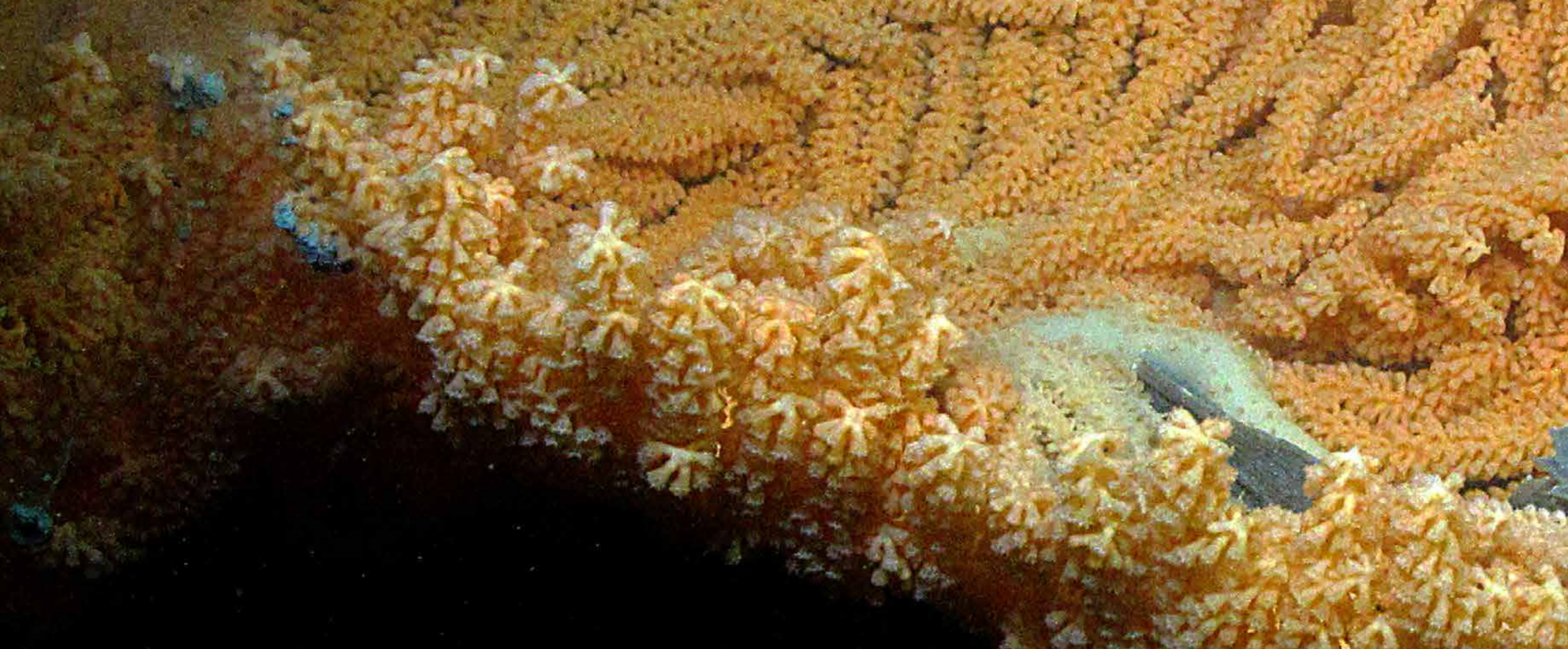
## ROV *SuBastian*

SOI's ROV engineering team worked closely with an international group of scientific advisors to develop ROV *SuBastian*, a robotic vehicle capable of working at depths as great as 4,500 m. After successful testing at the Monterey Bay Aquarium Research Institute, the team brought *SuBastian* onto *Falkor*. The ROV's imaging system includes state-of-the-art cameras capable of capturing 4K ultra-high-definition video. *SuBastian* imagery can be seen in the footage from the first science expedition in the Mariana back-arc. Four ROV cruises with *SuBastian* are planned for 2017.

## Artist-at-Sea Program

The year 2016 marked the first full year of the Artist-at-Sea program, with six artists invited to occupy berths of opportunity to work with scientists at sea. Resulting artwork includes analog photos treated with seawater to showcase the pH shift across the ocean, the first crocheted CTD data set, a piano composition based on *Falkor*'s underway data, a comic showing how scientists map the seafloor, and paintings that include overlays of mapping data. The artists' work is being shared at several gallery exhibits.

(right) Artist-at-sea Michelle Schwengel-Regala uses fibers to translate CTD data by knitting the entire data set onboard *Falkor*. *Photo credit: SOI/Monika Naranjo Gonzales*
(below) Artist-at-Sea Rebecca Rutstein superimposes sonar data into her paintings on *Falkor* during the transit from Vietnam to Guam, in June 2016. *Photo credit: SOI/Chris Linder*



# Epilogue

By Alan P. Leonardi and Robert D. Ballard

Humanity's future depends on understanding the ocean. We explore the ocean to make valuable scientific, economic, and cultural discoveries—and because ocean health and resilience are vital to our economy and to our lives. The Ocean Exploration Trust, the Schmidt Ocean Institute, and the NOAA Office of Ocean Exploration and Research are working together to reduce unknowns in our planet's deep ocean environments.

Exploration helps us to understand the incredible value of our ocean and its resources. Exploring these frontiers is too expensive and challenging for any single organization. Valuable public-private partnerships provide unique perspectives, diverse technological resources, and a broader range of expertise, while moving us forward with a sense of solidarity and collaboration.

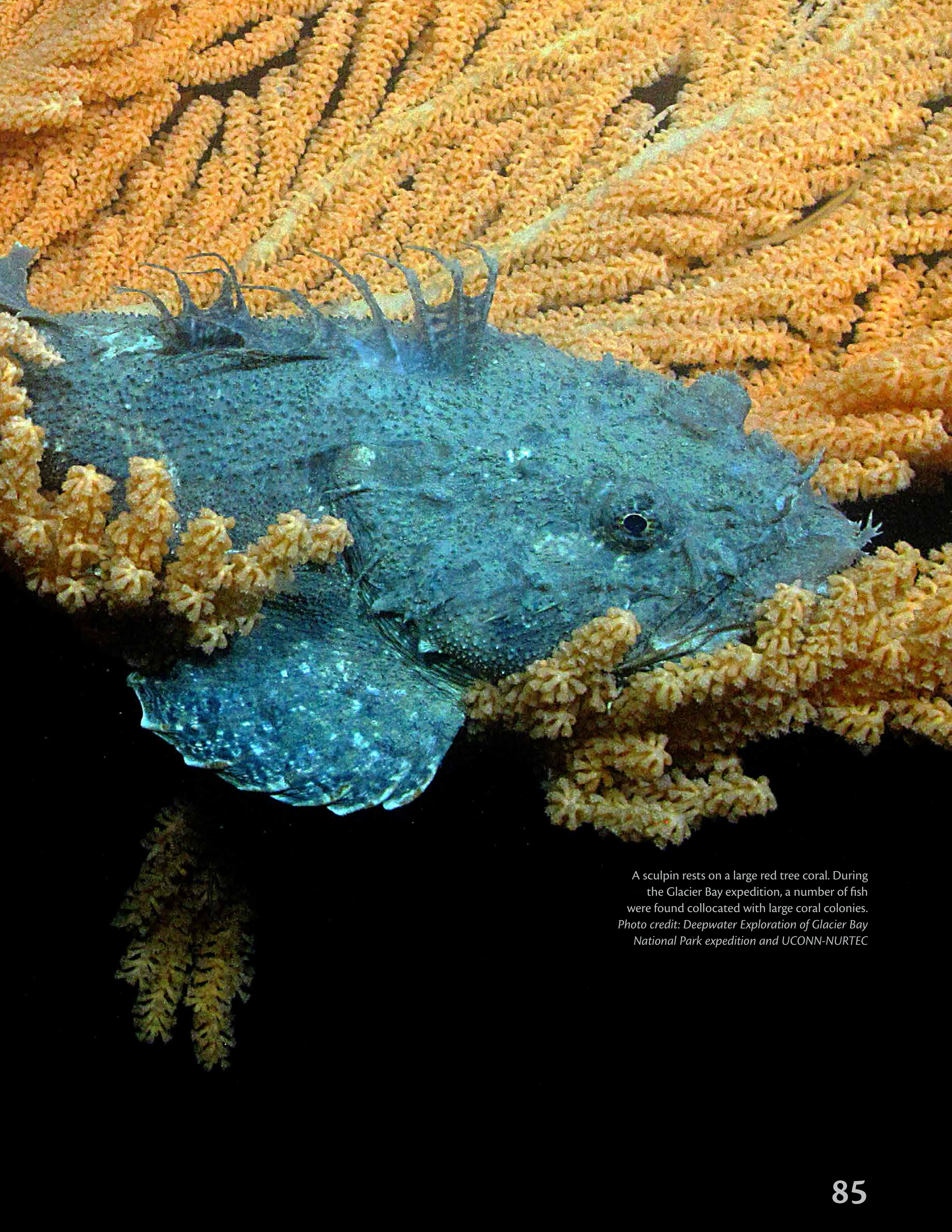
OET, SOI, and OER collect and provide high-value ocean data and information to the public. These organizations work with the broader science community to identify priority areas for exploration and research and to promote technological innovation to advance ocean exploration. Our collaborative model helps to inspire the next generation of ocean explorers, scientists, and engineers.

We are encouraged by continued developments in the oceanographic community. Advances in technology for ocean exploration allow us to reach new depths and previously unexplored areas. New partnerships forged with federal, academic, private, and nonprofit organizations allow us to seek innovative mechanisms to support ocean exploration over the long term, collect and provide baseline data, and contribute to understanding about resources and systems within both the US Exclusive Economic Zone and international waters. The publicly available data collected during our exploration expeditions and the research we fund gives resource managers the information they need to identify, understand, and manage ocean resources for the benefit of this and future generations.

Geological discoveries, novel species, and new understanding of deepwater environments exemplified the 2016 expeditions. OET, SOI, and OER operated in the Pacific Ocean to meet both NOAA and community-identified exploration priorities, including marine sanctuaries, monuments, and other protected areas. OET focused on priorities identified in the eastern Pacific, SOI concentrated on the central and western Pacific, and OER's work spanned the central Pacific to the Arctic.

In 2017, OET will continue operations in the eastern Pacific Ocean, SOI will conduct explorations from the southern Pacific to the Gulf of Alaska, and OER will conclude its third and final year of CAPSTONE in the central and western Pacific before launching a new exploration campaign in the Atlantic.

We realize that we have only begun to decipher our largely unknown ocean and recognize that much work and discovery still lie ahead. New exploration and research lead to a better understanding of the world around us, the discovery of new resources, and encouragement of young scientific minds. We are proud of our 2016 accomplishments and look forward to sharing the findings from upcoming expeditions in 2017 and beyond.



A sculpin rests on a large red tree coral. During the Glacier Bay expedition, a number of fish were found collocated with large coral colonies. *Photo credit: Deepwater Exploration of Glacier Bay National Park expedition and UCONN-NURTEC*

# Authors

(background photo) A purple crinoid hangs out on a dead coral stalk. *Photo credit: NOAA OER*

**Allan Adams** is Lecturer and Research Scientist, Massachusetts Institute of Technology, Cambridge, MA

**Diva J. Amon** is Postdoctoral Researcher, University of Hawai'i at Mānoa, Honolulu, HI

**Steve Auscavitch** is a graduate student at Temple University, Philadelphia, PA

**Robert D. Ballard** is President, Ocean Exploration Trust; Director, Center for Ocean Exploration, Graduate School of Oceanography, University of Rhode Island

**Kelsey Barnhill** is a graduate student at the South Dakota School of Mines and Technology, Rapid City, SD

**Tamara Baumberger** is NRC Postdoctoral Researcher, NOAA, Pacific Marine Environmental Lab, Newport, OR

**Kaitlyn Becker** is PhD Candidate, Harvard University, Cambridge, MA

**Katherine L.C. Bell** is Vice President, Exploration and Research, Ocean Exploration Trust, Narragansett, RI

**Deanna Bergondo** is Associate Professor, US Coast Guard Academy, New London, CT

**Don Blair** is Research Affiliate, MIT Media Lab, Cambridge, MA

**Margot Bohan** is Physical Scientist, NOAA, Office of Ocean Exploration and Research, Silver Spring, MD

**Amy Bowman** is Communications and Public Affairs Management Analyst, NOAA, Office of Ocean Exploration and Research, on contract through CollabraLink Technologies Inc., Silver Spring, MD

**Michael L. Brennan** is President, Brennan Exploration LLC, North Kingstown, RI

**Samantha Brooke**, NOAA, Pacific Islands Regional Office, Honolulu, HI

**Julie Bursek** is Education and Outreach Team Lead, NOAA, Channel Islands National Marine Sanctuary, Santa Barbara, CA

**Chris Caldow** is Research Coordinator, NOAA, Channel Islands National Marine Sanctuary, Santa Barbara, CA

**Frank Cantelas** is Marine Archaeologist, NOAA, Office of Ocean Exploration and Research, Silver Spring, MD

**Kasey Cantwell** is Field Operations Specialist, NOAA, Office of Ocean Exploration and Reseach, on contract through CollabraLink Technologies Inc., Silver Spring, MD

**Chris Castillo** is PhD Candidate, Stanford University, Palo Alto, CA

**Chin-Yi Cheng** is a graduate Student in the MIT Media Lab, Cambridge, MA

**Guy Cochrane** is Research Geophysicist, USGS, Pacific Coastal and Marine Science Center, Santa Cruz, CA

**Dwight Coleman** is Director, Inner Space Center, Graduate School of Oceanography, University of Rhode Island, Narragansett, RI

**Eric Collins** is Assistant Professor, University of Alaska Fairbanks

**James Conrad** is Geologist, USGS, Santa Cruz, CA

**Megan Cook** is Community STEM Program Coordinator, Ocean Exploration Trust, Narragansett, RI

**Marie-Helene Cormier** is Marine Researcher, University of Rhode Island, Narragansett, RI

**Emily Crum** is Online Communications Manager, NOAA, Office of Ocean Exploration and Research, on contract thru ERT Inc., Key West, FL

**James P. Delgado** is Director, Maritime Heritage Program, NOAA, Office of National Marine Sanctuaries, Silver Spring, MD

**Richard Dewey** is Associate Director, Science Services, Ocean Networks Canada, Victoria, BC, Canada

**Lea Edgar** is Archivist, Vancouver Maritime Museum, Vancouver, BC, Canada

**Kelley Elliott** is Expedition Coordinator, NOAA, Office of Ocean Exploration and Research, Silver Spring, MD

**Robert Embley** is Senior Research Geophysicist, NOAA, Pacific Marine Environmental Laboratory, Newport, OR

**Peter Etnoyer** is Marine Biologist, NOAA, Center for Coastal Environmental Health and Biomolecular Research, Charleston, SC

**Meredith Everett** is Postdoctoral Researcher, NOAA, Northwest Fisheries Science Center, Seattle, WA

**Gary Fabian** is Hydrographic Data Analyst, NOAA Affiliate, Austin, TX

**Christopher Figueroa** is a graduate student at the University of California Berkeley, Berkeley, CA

**Joanne Flanders** is Engagement Advisor, NOAA, Office of Ocean Exploration and Research, Silver Spring, MD

**Mike Ford** is Oceanographer, NOAA, National Marine Fisheries Service, Silver Spring, MD

**Ryan Freedman** is Research Operations Specialist, NOAA, Channel Islands National Marine Sanctuary, Santa Barbara, CA

**Patricia Fryer** is Professor, University of Hawai'i at Mānoa, Honolulu, HI

**Allison Fundis** is VP of Education, Outreach & Communications, Ocean Exploration Trust, Narragansett, RI

**Peter Girguis** is Professor, Harvard University, Cambridge, MA

**Gonzalo Giribet** is Professor, Harvard University, Cambridge, MA

**Deborah Glickson** is Senior Program Officer, Board on Earth Sciences and Resources/Water Science and Technology Board, The National Academies

**Susan Gottfried** is Data Management Coordinator, NOAA, National Centers for Environmental Information, Stennis Space Center, MS

**Stephen Hammond** is Senior Scientist, NOAA, Office of Ocean Exploration and Research, on contract through ERT Inc., Portland, OR

**Russell Hopcroft** is Professor, University of Alaska Fairbanks

**Jonathan Howland** is Senior Engineer, Woods Hole Oceanographic Institution, Woods Hole, MA

**Katrin Iken** is Professor, University of Alaska Fairbanks

**Jonathan Jackson** is Project Scientist, NOAA, National Centers for Environmental Information, Stennis Space Center, MS

**Dhruv Jain** is a recent SM graduate of the MIT Media Lab, Cambridge, MA

**Jennifer Jencks** is Physical Scientist, NOAA, National Centers for Environmental Information, Denver, CO

**Donald L. Johnson** is Professor, University of Nebraska-Lincoln, Lincoln, NE

**Renato Kane** is Lead Navigator and Data Manager, Ocean Exploration Trust, Narragansett, RI

**Paula Keener** is Education Lead, NOAA, Office of Ocean Exploration and Research, Charleston, SC

**Christopher Kelley** is Program Biologist, University of Hawai'i at Mānoa, Honolulu, HI

**Brian R.C. Kennedy** is Expedition Coordinator, NOAA, Office of Ocean Exploration and Research, on contract through University Corporation for Atmospheric Research, Elon, NC

**James Kennett** is Professor Emeritus, University of California Santa Barbara, Santa Barbara, CA

**Jeremy R. Kinney** is Curator, Smithsonian Institution National Air and Space Museum, Washington, DC

**Simon L. Klemperer** is Professor, Stanford University, Stanford, CA

**Vanessa Knutson** is a graduate student at Harvard University, Cambridge, MA

**Jasper Konter** is Associate Professor, University of Hawai'i, Honolulu, HI

**Randall K. Kosaki**, NOAA Office of National Marine Sanctuaries, Honolulu, HI

**Ian Kulin** is Associate Director, Marine Operations, Ocean Networks Canada, Victoria, BC, Canada

**Daniel Larsh** is Post Production Supervisor, Ocean Exploration Trust

**Mark Legg** is President, Legg Geophysical Inc.

**Alan P. Leonardi** is Director, NOAA, Office of Ocean Exploration and Research, Silver Spring, MD

**Stephen Licht** is Assistant Professor, University of Rhode Island, Kingston, RI

**Megan Lickliter-Mundon** is PhD Candidate, Texas A&M University, College Station, TX

**Elizabeth Lobecker** is Physical Scientist, NOAA, Office of Ocean Exploration and Research, on contract through ERT Corporation, Durham, NH

**Lawrence L. Lovell** is Senior Biologist, County Sanitation Districts Los Angeles County, Los Angeles, CA

**Megan Lubetkin** is a recent graduate of Bates College, Lewiston, ME

**Duncan MacLeod** is Curator, Vancouver Maritime Museum, Vancouver, BC, Canada

**Mashkoor Malik** is Physical Scientist, NOAA, Office of Ocean Exploration and Research, Silver Spring, MD

**Jacques Marc** is Past President, Underwater Archaeological Society of British Columbia, Victoria, BC, Canada

**Jeffrey Marlow** is Postdoctoral Researcher, Harvard University, Cambridge, MA

**Sarah Marquis** is West Coast/Pacific Media Coordinator, NOAA, Office of National Marine Sanctuaries, Orange County, CA

**Ashley Marranzino** is a graduate student at the University of Rhode Island, Kingston, RI

**Leigh Marsh** is Postdoctoral Research Fellow, National Oceanography Centre, University of Southampton, Southampton, UK

**Catalina Martinez** is Regional Program Manager, NOAA, Office of Ocean Exploration and Research, Narragansett, RI

**Russell Matthews** is Aviation Historian, NOAA, Office of National Marine Sanctuaries, Silver Spring, MD

**David McKinnie** is Engagement Lead (acting), NOAA, Office of Ocean Exploration and Research, Seattle, WA

**Susan Merle** is Senior Research Assistant, Oregon State University and NOAA, Pacific Marine Environmental Laboratory, Newport, OR

**Sharon Mesick** is NCEI Information Services Division Chief, NOAA, National Centers for Environmental Information, Stennis Space Center, MS

**Kate Moran** is President & Chief Executive Officer, Ocean Networks Canada, Victoria, BC, Canada

**Kelly Moran** is Production Coordinator, Ocean Exploration Trust, Narragansett, RI

**William Mowitt** is Deputy Director, NOAA, Office of Ocean Exploration and Research, Silver Spring, MD

**Scott Munro** is Executive Producer, Media Productions, Ocean Exploration Trust, Narragansett, RI

**Sarah E. Myhre** is Postdoctoral Researcher, University of Washington, Seattle, WA

**Amanda Netburn** is a John A. Knauss Sea Grant Fellow, NOAA, Office of Ocean Exploration and Research, Silver Spring, MD

**Jifei Ou** is PhD Candidate, MIT Media Lab, Cambridge, MA

**Dorothy Pak** is Project Scientist, University of California Santa Barbara, Santa Barbara, CA

**Michael Parke** is Research Fish Biologist, NOAA, Pacific Islands Fisheries Science Center, Honolulu, HI

**Frank Parrish** is Division Director, Protected Species Division, NOAA, Pacific Islands Fisheries Science Center, Honolulu, HI

**Brennan Phillips** is Postdoctoral Fellow, Harvard University, Cambridge, MA

**Christina Piotrowski** is Collection Manager, California Academy of Sciences, San Francisco, CA

**Shirley A. Pomponi** is Executive Director, NOAA Cooperative Institute for Ocean Exploration, Research and Technology/CIOERT, Harbor Branch Oceanographic Institute at Florida Atlantic University, Ft. Pierce, FL

**Jeremy Potter** is Expeditions Lead, NOAA, Office of Ocean Exploration and Research, Silver Spring, MD

**Susan Poulton** is Media Relations Consultant, Door 44 Digital

**Nicole Raineault** is Director of Science Operations, Ocean Exploration Trust, Narragansett, RI

**Evan Reger** is Staff Naval Architect, US Coast Guard Marine Safety Center, Washington, DC

**Jan Roletto** is Research Coordinator, Greater Farallones National Marine Sanctuary, San Francisco, CA

**Adrian Round** is Director, Observatory Operations, Ocean Networks Canada, Victoria, BC, Canada

**Craig Russell** is Program Manager, *Okeanos Explorer* Expeditions, NOAA, Office of Ocean Exploration and Research, Seattle, WA

**Richard Sanders** is Professor, US Coast Guard Academy, New London, CT

**Will Sautter** is Marine GIS Analyst, NOAA, National Centers for Coastal Ocean Science, Silver Spring, MD

**Wendy Schmidt** is Co-founder, Schmidt Ocean Institute, Palo Alto, CA

**Robert V. Schwemmer** is West Coast Regional Coordinator, Maritime Heritage, NOAA, Office of National Marine Sanctuaries, Santa Barbara, CA

**Sarah Seabrook** is a graduate student at Oregon State University, Corvallis, OR

**Stephanie Sharuga** is Gulf Research Program Science Policy Fellow, The National Academies of Sciences, Engineering, and Medicine, Lafayette, LA

**Derek Sowers** is Physical Scientist, NOAA, Office of Ocean Exploration and Research, on contract through ERT Corporation, Durham, NH

**Misha Sra** is PhD Candidate, MIT Media Lab, Cambridge, MA

**Matthew Stout** is Chief of Staff, NOAA, Office of National Marine Sanctuaries, Silver Spring, MD

**Katherine Sutton** is STEM Education Specialist, Ocean Exploration Trust, Narragansett, RI

**Lisa J. Symons** is Resource Protection Coordinator, NOAA, Office of National Marine Sanctuaries, Silver Spring, MD

**Mitchell Tartt** is Chief, Conservation Science Division, NOAA, Office of National Marine Sanctuaries, Silver Spring, MD

**Jonathan Tree** is a graduate student at the University of Hawai'i at Mānoa, Honolulu, HI

**Hans Van Tilburg** is Maritime Heritage Coordinator, NOAA, Office of National Marine Sanctuaries, Honolulu, HI

**Anthony Tully** is Historian and Managing Editor, combinedfleet.com, Dallas, TX

**Kai Vetter** is Professor, University of California Berkeley, Berkeley, CA

**Daniel Wagner** is Research Specialist, NOAA, National Centers for Coastal Ocean Science, Charleston, SC

**Jamie Wagner** is a graduate student at Duke University, Durham, NC

**Katie Wagner** is Communications and Public Affairs Management Analyst, NOAA Office of Ocean Exploration and Research, on contract through CollabraLink Technologies Inc., Silver Spring, MD

**Carrie Wall-Bell** is Research Scientist, University of Colorado at Boulder, in support of NOAA, National Centers for Environmental Information

**Rhian Waller** is Associate Professor, University of Maine, Walpole, ME

**Gary Williams** is Curator, California Academy of Sciences, San Francisco, CA

**Samantha Wishnak** is Digital Media Coordinator, Ocean Exploration Trust, Narragansett, RI

**Alexandra Witten** is Director of Grants & Stewardship, Ocean Exploration Trust, Narragansett, RI

**Lining Yao** is PhD Candidate, MIT Media Lab, Cambridge, MA

**Victor Zykov** is Director of Research, Schmidt Ocean Institute, Palo Alto, CA (background photo) Octopus in Arena Canyon. *Photo credit: OET*

# Acknowledgments


## Ocean Exploration Trust

### NAUTILUS EXPLORATION PROGRAM STAFF

- Tami Ames[75], Travel and Logistics Support Assistant
- Robert Ballard[75, 123], President
- Katherine L.C. Bell[75], Vice President, Exploration & Research
- Stephanie Bewley[75], Controller
- Michael Brennan[75], Director, Marine Archaeology & Maritime History
- Joshua Chernov[75], Interim Manager, ROV Operations
- Dwight Coleman[124], Director, Inner Space Center
- Megan Cook[75], Coordinator, Community STEM Programs
- Allison Fundis[75], Vice President, Education, Outreach & Communications
- Samuel Garson[75], Coordinator, Education Programs
- Ethan Gold[75], Director, Software & Data Engineering
- Robert Knott[75], Senior Video Engineer
- Ian Kulin[75], Port Engineer
- Daniel Larsh[75], Post-Production Supervisor & Editor
- David LePage[75], Video Engineer
- Melinda Linzey[75], Finance Associate
- Justin Lowe[75], Data Engineer
- Kay McConagha[75], Chief Financial & Administrative Officer
- Janice Meagher[75], Executive Administrator
- Kelly Moran[75], Production Assistant
- Scott Munro[75], Executive Producer
- Angela Murphy[75], Coordinator, Travel & Logistics
- Susan Poulton[75], Digital Media Consultant
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- Chris Roman[123], Director, Mapping & Imaging Program
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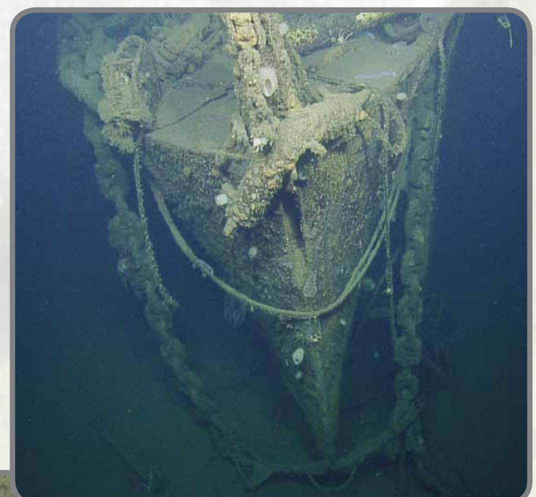

Towing bridle on the bow of USS *Independence.* *Photo credit: OET*

Sculpin in Arena Canyon. *Photo credit: OET*

# NOAA Office of Ocean Exploration and Research

The 2016 NOAA Office of Ocean Exploration and Research expeditions were pivotal, achieved through a dynamic network of people, platforms, and partners. The work of exploration has become increasingly interconnected and carries new challenges and opportunities to increase its pace, scope, and efficiency. OER is the only federal organization dedicated to exploring the deep ocean. The enormity of that responsibility was well matched in 2016, with a collaborative network of several hundred people, across seven thematic areas, with expertise in at-sea and shoreside operations; science and technology; data management; education, outreach, and media; and administrative requirements. This network has improved US technical capability and provided baseline information upon which future work will be built, work that catalyzes and informs resource management decisions including fisheries, energy, minerals, and conservation. Stepping into 2017, OER acknowledges this state-of-the art network as it advances US ocean exploration forward through new approaches, new ideas, and new possibilities.

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(background photo) ROV *Deep Discoverer* images a newly discovered hydrothermal vent field at Chammoro Seamount. *Photo credit: NOAA OER*

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ROV *Hercules* examining the seafloor of Pioneer Canyon. *Photo credit: OET*

Gun turret on USS *Independence.* *Photo credit: OET*

A close-up of bamboo coral polyps on an unnamed seamount just outside Papahānaumokuākea Marine National Monument. *Photo credit: NOAA OER*


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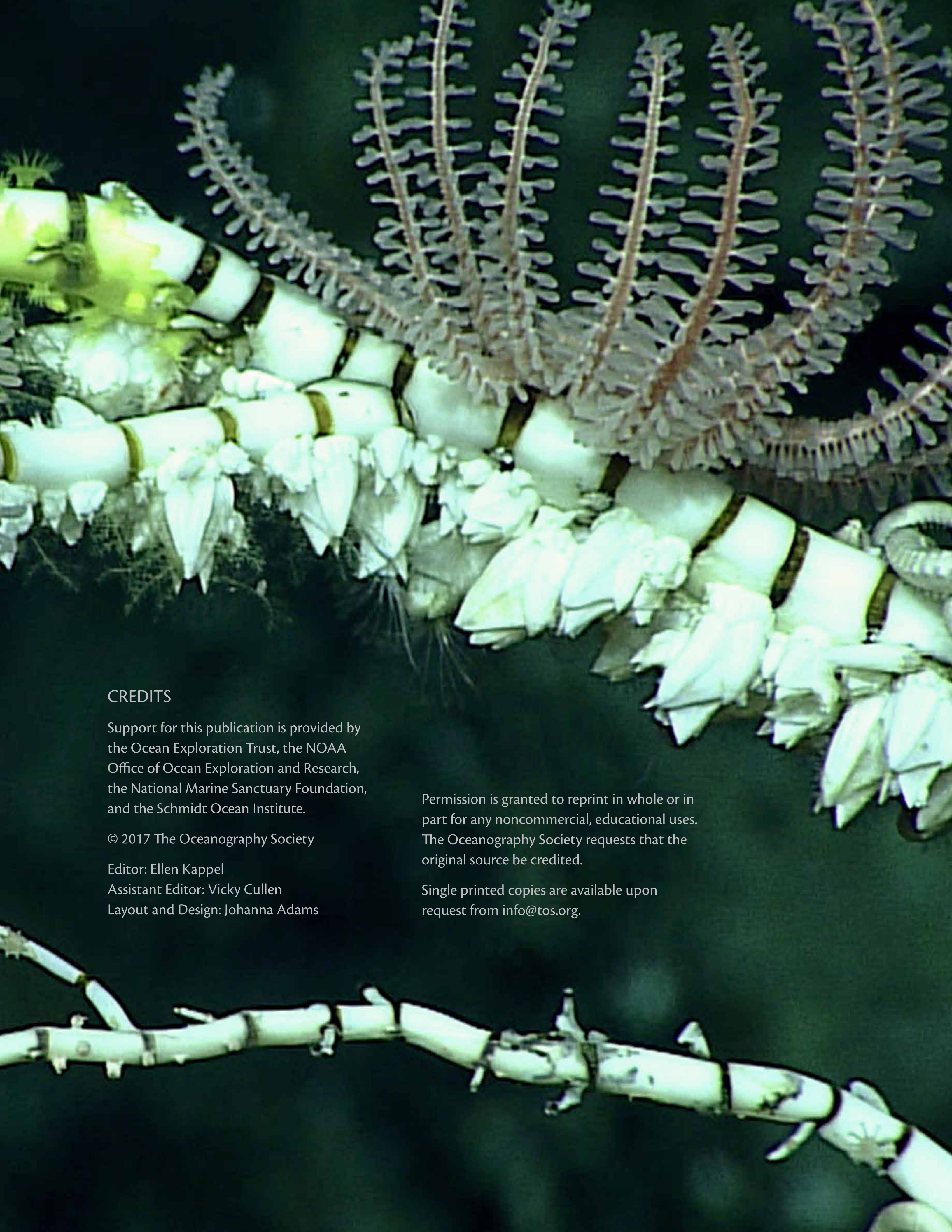
# Acronyms

ADCP....................... Acoustic Doppler current profiler
CAPSTONE ............ Campaign to Address Pacific monument Science, Technology, and Ocean NEeds
CINMS..................... Channel Islands National Marine Sanctuary
CNMI....................... Commonwealth of the Northern Mariana Islands
CTD......................... Conductivity, temperature, depth sensor
ECC......................... Exploration Command Center
ECS......................... Extended Continental Shelf
E/V.......................... Exploration Vessel
GFNMS.................... Greater Farallones National Marine Sanctuary
GUI.......................... Graphical User Interface
LDEO ...................... Lamont-Doherty Earth Observatory of Columbia University
NCEI ....................... NOAA's National Centers for Environmental Information
NMFS...................... NOAA's National Marine Fisheries Service
NOAA ..................... National Oceanic and Atmospheric Administration
MBNMS................... Monterey Bay National Marine Sanctuary
Mbps ....................... Megabits per second
MPA ........................ Marine Protected Area
MTMNM................. Marianas Trench Marine National Monument
OER......................... NOAA's Office of Ocean Exploration and Research
OET ......................... Ocean Exploration Trust
ONC ........................ Ocean Networks Canada
PCZ.......................... Prime Crust Zone
PMNM.................... Papahānaumokuākea Marine National Monument
PRIMNM................. Pacific Remote Islands Marine National Monument
ROV......................... Remotely operated vehicle
R/V .......................... Research Vessel
SOI........................... Schmidt Ocean Institute
S/S............................ Single-screw Steamship
STEM ...................... Science, technology, engineering, and mathematics
UNESCO ................ United Nations Educational, Scientific, and Cultural Organization
UNH........................ University of New Hampshire
USGS....................... United States Geological Survey
USS .......................... United States Ship
WHOI ..................... Woods Hole Oceanographic Institution

(background photo) Brisingids are a group of sea star that lives exclusively in the deep-sea (>200 m to 6,000 m water depth). This one, a *Novodinia*, is taking advantage of its perch on a dead bamboo coral branch to feed on crustaceans being carried by in the current. *Photo credit: NOAA OER*



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Layout and Design: Johanna Adams



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LT Tara Elliott sits an ROV watch on a dive in the Greater Farallones National Marine Sanctuary aboard E/V *Nautilus*. *Photo credit: OET*

Limpet, shrimp, and crabs gather around a hydrothermal vent 3,500 m deep in the Mariana back-arc. *Photo credit: SOI*

Expedition Science Leads Daniel Wagner (foreground) and Jonathan Tree (background) take a look at collected samples. *Photo credit: NOAA OER*

THE OCEANOGRAPHY SOCIETY

**PO Box 1931**
**Rockville, MD 20849-1931 USA**
**info@tos.org | https://tos.org**